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SPATIAL AND TEMPORAL VARIABILITIES IN UNDERWATER ACOUSTIC TRANSMISSION: AN ANALYTICAL REVIEW

by

HASSAN B. ALI

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SPATIAL AND TEMPORAL VARIABILITIES IN UNDERWATER ACOUSTIC TRANSMISSION: AN ANALYTICAL REVIEW

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This memorandum has been prepared within the SACLANTCEN Underwater Research Division as part of Project 05.

O.F. Hastrup

O.F. HASTRUP
Division Chief

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SPATIAL AND TEMPORAL VARIABILITIES IN UNDERWATER ACOUSTIC TRANSMISSION: AN ANALYTICAL REVIEW

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Hassan B. Ali

ABSTRACT

An overview of temporal and spatial variability in underwater acoustic transmission is provided, based on a literature survey of previous experimental studies. Following comments on the use of the term "fluctuations", the medium-induced degradations of a transmitted signal are described and general approaches to medium (channel) characterization are discussed. The use of the scattering-function technique and the alternative, but equivalent, wide-sense stationary uncorrelated scattering (WSSUS) channel approach are considered, using experimental results to demonstrate the utility and the limitations of these methods. Following ~~brief~~ remarks on the effect of acoustic fluctuations on sonar performance, examples of environmental and acoustic fluctuations are provided. In conformity with current practice, the temporal and spatial scales of ocean variability are analyzed in terms of: (1) a mean vertical profile representing local climatology; (2) a mesoscale component that is deterministic on the acoustic time scale; and (3) a statistical component representing smaller scale, random fluctuations due to internal waves and fine structure. Each component is discussed, ~~at length,~~ using experimental results from several sources. Tidally induced fluctuations are discussed separately, followed by some comments on the significant effects due to source/receiver motions. Recommendations are given on several areas of acoustic transmission fluctuations that warrant further investigation.

INTRODUCTION

The topic of underwater acoustic fluctuations has been the subject of investigation for several decades. World War II, in particular, saw intensive activity in acoustic fluctuations research, motivated largely by underwater warfare (sonar) considerations. The summary written by Eckart and Carhart in 1950 <1> is still a useful classic on the subject.

In recent years renewed interest has been generated by the increased importance of ASW and the greater flexibility and power of sonar processing, as well as by progress in underwater telemetry and acoustic communications. As a consequence of the above, the literature on acoustic transmission fluctuations is quite large. Urick <2> cites a recent (1976) bibliography that lists 132 references to the subject. In spite of the plethora of data (and theories to explain them) there are still many unanswered questions. For example, while a number of fluctuation mechanisms have been proposed, it has been difficult, or impossible in some cases, to separate these causes in many experiments. Further, experimental differences in the investigations have sometimes led to seemingly contradictory results. In addition, some important areas have as yet received relatively little attention. For example, there still exists a need for a better understanding of the acoustic transmission-loss fluctuations inherent in long-range, low-frequency propagation. Deficiencies in other areas have also become apparent from this survey; possible remedies are discussed in the final chapter of this memorandum.

Before giving examples of environmental and acoustic fluctuations it is worthwhile to make some comments on what is to be understood by the word "*fluctuations*". It seems that "fluctuations" is one of those concepts that means different things to different investigators: what may be considered a fluctuating signal in one case may be regarded as a steady-state signal in another application. Tidally induced diurnal variations in transmission loss may not be considered to be fluctuations to a sonar processor whereas temporal variations of duration of up to seconds or minutes would be. Urick <2> defines fluctuations or "temporal" coherence, as "...changes in the signal received by a single hydrophone, relative to a steady source, over a period of time." He defines spatial coherence as "... the changes occurring between spatially separated hydrophones." Unless one quantifies "changes", these definitions become become so general as to classify practically all measurement results as fluctuations. An earlier and more quantitative definition is due to Carhart and Eckart <1>. Recognizing the broad range in time scales of transmission variability, they make a distinction between the various frequency ranges of fluctuations. In particular, they define "distortion", "fluctuation", and "variation" as follows (see Fig. 1):

> "Distortion" refers to amplitude changes in the transmitted signal during a time less than 0.1 s; this arises from their observations that a 100 ms pulse appeared distorted on reception.
>
> "Fluctuation" is reserved for changes in average amplitude of duration between 0.1 s and ½ hour, based on observed amplitude changes in a series of pings lasting ½ hour or less.
>
> "Variation" is used for longer period changes.

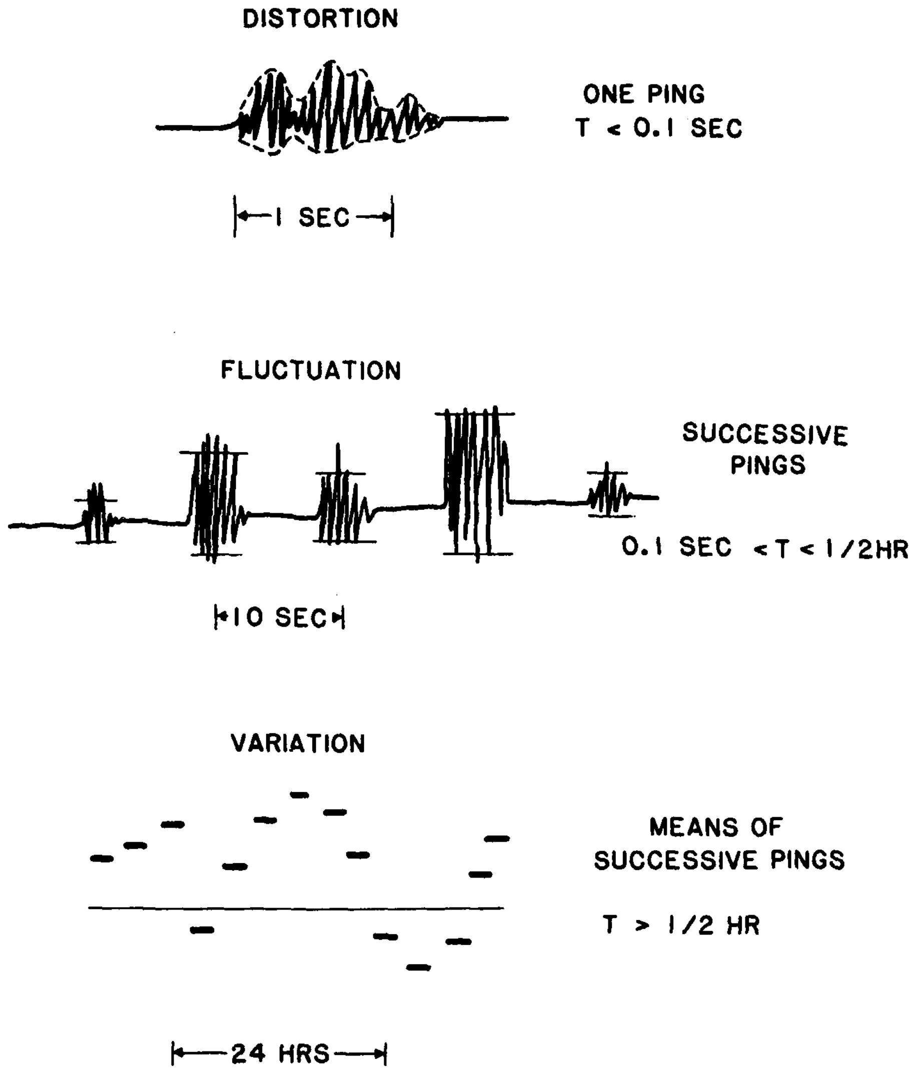


FIG. 1 TEMPORAL FLUCTUATION TERMINOLOGY (From <3>)

Although the preceding definitions were based entirely on their utility in describing the Carhart/Eckart experiments, they are still of some usefulness today. Another description is provided by the "fluctuation spectrum" (Fig. 2) given by Urick <3>; this represents the "fluctuation power per cycle of frequency, referred to the average power of the 'carrier' - that is, of whatever is doing the fluctuating." The curve thus represents the magnitude and rapidity of the fluctuation, and its integral from zero to infinity represents the square of the modulation index. Further, the output power of a low-pass filter following a square-law detector is simply the integral of the curve out to the reciprocal of the integration time of the low-pass filter, multiplied by the average carrier power.

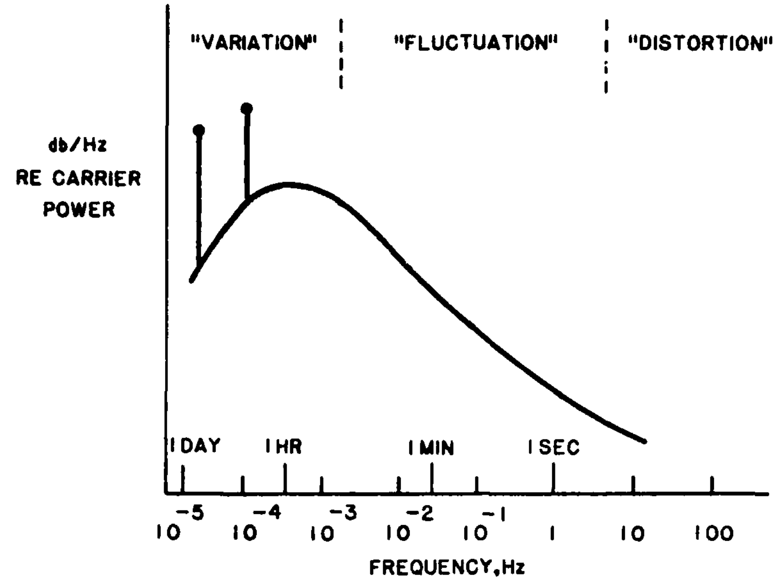


FIG. 2 NORMALIZED FLUCTUATION POWER SPECTRUM (From <3>)

It is noted that in the preceding definitions the variations have been explicitly assumed to be temporal in nature. Unfortunately, the restriction of the term "fluctuations" to the designation of temporal variations is not widespread. On the contrary, it is more common to allow the term to mean either temporal or spatial variations, or both. In particular, the terms "temporal fluctuations" and "spatial fluctuations" are used by numerous investigators, including Sykes <4>, Dugan <5>, Brekhovskikh <6>.

In particular measurements it is often not clear, a priori, whether the variations in received acoustic signals are to be attributed to spatial or to temporal variability in the medium. A brief discussion of transmission-loss measurements should clarify the situation. In principle, the spatial variations in transmission loss can be best determined by simultaneous measurements of the sound pressure at a sufficient number of points along the sound path and over the region of interest. Simultaneous time series from each measurement location will then provide the temporal variation of the transmission loss. In practice, the large area of interest for propagation loss (hundreds to thousands of kilometres) makes such a procedure unfeasible. Instead, spatial variations in transmission loss are usually studied by using towed projectors - or sound sources deployed at different ranges - and fixed receivers. The received signals thus obtained will clearly display both temporal variations and spatial variations that, depending on the towing speed, source deployment interval, and environment, may not be easily separable. An appropriate time averaging, however, will provide the mean transmission loss as a function of range. Temporal variations are best obtained in fixed-source, fixed-receiver geometries with continuous wave (cw), periodic sequence, or explosion-generated signals. Generally, both spatial and temporal variations in transmission loss are of interest: the former for determining maximum detection ranges and optimum hydrophone array design, for example, and the latter for designing signal processors and predicting system performances.

The term "fluctuations" is thus used quite flexibly, depending on the particular application, to denote either temporal variations or spatial variations. In the interest of clarity, it would probably be preferable to restrict the term to denote temporal variations, consistent with its original Latin origins. In particular, one should understand by the expression "fluctuations" those temporal deviations from "frozen-medium" transmission that are significantly greater than could be expected from normal experimental errors. We avoid the trap of trying to explain what constitutes "significant deviations", preferring instead to allow each experimental situation to provide its own answer.

Although helpful, the preceding does not completely solve the problem, since "temporal deviations" can include a rather large number of phenomena, many of which would not be considered fluctuations by some. For example, the temporal variations at a fixed point caused by seasonal changes are not considered to be fluctuations by some investigators. Nor are the variations in acoustic response caused by changing multipath propagation, or by source motion, or by changes in location relative to convergence zones, and so forth. Clearly, even in an identical environment, a given receiver may reveal markedly greater "fluctuations" than another if one receiver is omnidirectional while the other is highly directional. These instrument-related fluctuations, as it were, although of no less significance to a sonar operator, are nevertheless of a different nature from the medium-induced fluctuations. Is it reasonable, then, to include the manifestations of a host of different underlying phenomena under the one term, "fluctuations"? Perhaps not, but there seems to be a tendency in the literature to do precisely this. Although a definition of general validity would be best, it is probably unrealistic to expect more than one of narrower application, since particular measurements are usually conducted with limited objectives. Regrettably, even the latter modest wish is rarely granted: too often the performer of complex experiments and lengthy analyses on fluctuations takes it for granted that the meaning of "fluctuations" is obvious. In the following, no attempt is made to solve this problem of terminology. That is not the purpose of this report. However, wherever possible, the term "fluctuations" will be used only to denote temporal variations, regardless of their causes, and not be used for spatial variations.

In passing, it is noted that the fluctuation studies cited above make no explicit mention of fluctuations in the phase of the transmitted signal. Indeed, only in recent years has the importance of phase as a reflection of environmental fluctuations been appreciated. This is due, in part, to the earlier unavailability of adequate phase-measurement equipment (particularly stable-drive oscillators and "frequency-lockable" receivers). On the importance of phase, more is said later.

1 THE BASIC ACOUSTIC PROBLEMS IMPOSED BY THE VARIABILITY OF THE MEDIUM

Simply stated, the basic problem in attempting to use sound in the sea is that the parameters controlling the propagation are subject to change, and that these changes are usually unpredictable, and almost always unfavourable to the user. As stated in <1>, "...if sound of constant intensity and frequency is transmitted through the sea from one ship and received on another at some fixed distance, the intensity of the signal from one second to the next will not be constant; it fluctuates, often by a factor of ten. Indeed, the presence of fluctuation is perhaps the most constant characteristic of sound in the sea."

More particularly, the medium causes a pure tone signal to become spread in frequency and an impulse signal to be spread (stretched) in time, as illustrated in Fig. 3. In the more usual case, in which the transmitted signal has a finite duration, T, and a bandwidth, W, the received signal will be of duration L+T and bandwidth W+B. Here L is the multipath time delay and B is the so-called doppler spread. To achieve little or no distortion over the bandwidth of a signal, i.e., non-frequency selective or flat fading, the bandwidth must be much less than the reciprocal of the time spread, L:

$$W \ll 1/L.$$

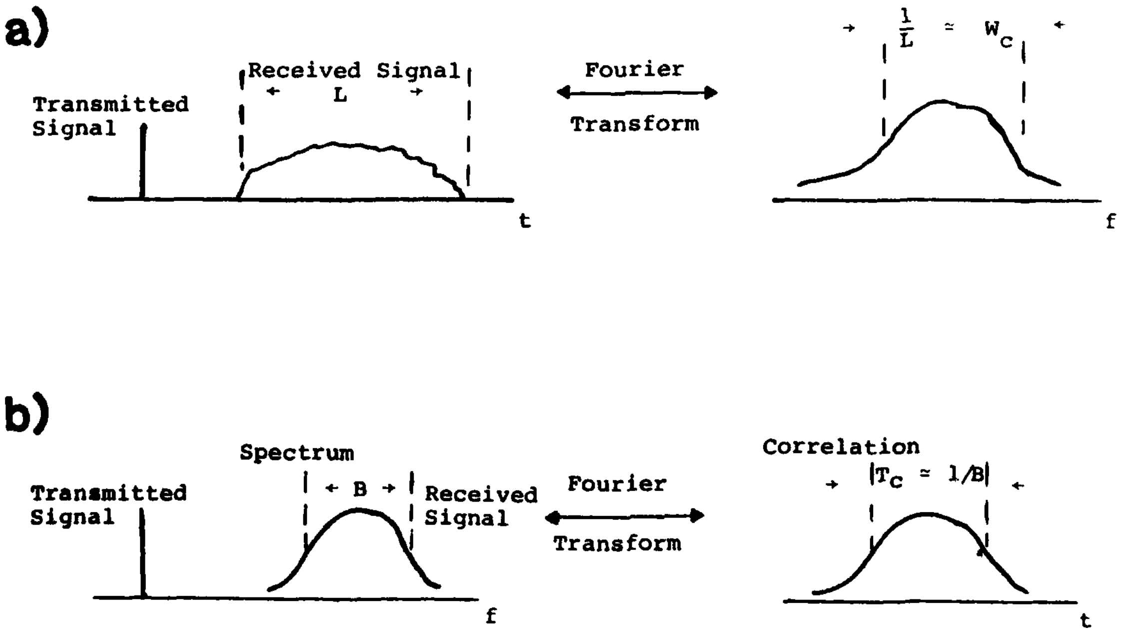


FIG. 3 TIME AND FREQUENCY DISPERSION (From <12>)
a) Time dispersion (multipath spread).
b) Frequency dispersion (doppler spread).

Otherwise, unequal attenuation of the (fourier) component frequencies takes place, resulting in signal distortion. Thus the reciprocal time spread is a measure of the coherence bandwidth, Wc, of the fading process. Similarly, a signal of time duration T will suffer little or no distortion, i.e., will experience time-flat fading, if its duration is much less than the fading rate due to doppler:

$$T \ll 1/B$$

Reciprocal frequency spread is thus a measure of the coherence time (or correlation time), Tc.

Although it is possible for a propagation channel to be dispersive in only one domain – for example, only time-dispersive or only frequency-dispersive – the underwater acoustic channel is a doubly-spread channel. Therefore, if a received signal is to be undistorted (flat-flat fading), the following must hold:

$$W \ll 1/L \quad \text{and} \quad T \ll 1/B.$$

Since $WT \geqq 1$ for all signals (actually, so-called "spread-spectrum" communication systems employ a bandwidth much larger than the reciprocal of the signal duration in order to resolve multipath arrivals), the preceding requires the spread factor, BL, to be less than unity for undistorted signals:

$$BL \ll 1.$$

The implications of the preceding condition are clear: in order to estimate the channel response one must observe the channel output for at least L seconds; on the other hand, a fading rate of 1/B seconds implies that the channel response changes in times of the order of 1/B seconds. Hence 1/B must be much larger than L if an adaptive signal-processing scheme is to be successful. When $BL < 1$, the channel is said to be underspread.

In the preceding, no explicit mention is made of signal distortion caused by phase shifts. Clearly, however, the amplitude and phase response of a given linear system (e.g. the ocean) are interrelated. In particular, one recalls from elementary linear systems theory <7>, that a distortionless-transmission system requires uniform amplitude and linear - phase-shift characteristics over the frequencies covered by the signal. If either one (or both) of these requirements is not met, signal distortion results. Naturally, in practice, these requirements are not, in fact cannot, be satisfied since they result in physically unrealizable systems. However, if the system bandwidth is larger than the signal bandwidth and results in phase shifts linearly proportional to frequency, the transmitted signal will suffer little distortion. Moreover, in this case, the distortion will be symmetrical about a delay time equal to the slope of the filter phase characteristics. Non-linear phase characteristics will result in non-symmetrical distortion.

In practice, the degradations in system performance resulting from signal distortion are dependent also on the requirements of the system. If, for example, signal fidelity is not of primary interest – as for example in certain digital communication systems or in search-radar systems, in which a merely recognizable pulse suffices – then greater distortion (and smaller

system bandwidths) can be tolerated. On the other hand, signal distortion is more troublesome for systems requiring high-fidelity signals, such as for tracking radars, in which the arrival time of individual pulses must be accurately determined.

2 METHODS OF CHARACTERIZING THE SOUND CHANNEL

In principle, as Ch. 1 has shown, one can characterize the sound channel in the underwater medium by time (range) and frequency (doppler) spreading, L and B, respectively. (It is noted, in passing, that for some problems, such as echo ranging, one is concerned, in addition, with characterizing the transmitted signal and the "target", since the interaction between these constitutes the problem.) Regrettably, the problem is not as easy as might be guessed at first sight, since values of L and B are not, in general, easy to come by. Values have been obtained for particular geographical regions under particular environmental and experimental conditions. Further, in simple cases, it is even possible to calculate some values for L and B.

2.1 Scattering-Function Approach

More precisely, one attempts to measure and/or calculate the scattering function for the medium, from which B and L may be deduced. The scattering function describes the manner in which a transmitted signal is distributed in time (range) and frequency (doppler). As may be suspected, the scattering function is related (via a two-dimensional fourier transform) to correlation functions of the received signal. In particular, the scattering function, $S(\xi,\upsilon)$ for a doubly-dispersive medium can be expressed in terms of the "two-frequency correlation function", $R(\Omega,\tau)$, as

$$S(\xi,\upsilon) = \iint R(\Omega,\tau)e^{-i2\pi(\xi\Omega-\upsilon\tau)}\,d\tau\,d\Omega,$$

where ξ is a range (time) variable, υ represents doppler frequency, and τ is time delay. The two-frequency correlation function is a commonly used description for propagation channels, defined as the ensemble average of the varying channel transfer function, $H(f,t)$; i.e.,

$$R(\Omega,\tau) = E[H^*(f,t)\;H(f+\Omega,\;t+\tau)],$$

where E denotes the ensemble average, Ω represents the frequency separation between two transmitted sinusoids, and the asterisk denotes the operation of complex conjugation. Thus the two-frequency correlation function indicates the correlation in the response to two transmitted sinusoids, thereby providing a measure of signal distortion. As indicated earlier, the parameters B and L, discussed qualitatively above, can be quantitatively expressed in terms of the scattering function, $S(\xi,\upsilon)$. Kennedy <8> gives details. Alternative formulations of the scattering function are also possible <8,9,10,11>.

The scattering-function approach models the ocean medium as a scattering source. The received signal is thus envisioned as the superposition of signals scattered from a large number of independent, moving scatterers. Because of the number of scatterers and the large fluctuations in received amplitudes and phases, it is assumed that the received signals are statistically independent random variables. Experimental evidence suggests further that the received process is often zero-mean gaussian with a Rayleigh-fading envelope and a uniformly distributed phase. Hence the process can be completely characterized by correlation functions of the received signals.

A sketch of what a rather simple scattering function might look like for a three-path propagation channel is given in Fig. 4 <12>. In this case, the travel times of the different propagation paths are different enough to produce distinct areas of energy concentration; that is, to produce a tri-modal scattering function. Since the surface paths would generally suffer a greater doppler shift than the deeper refracted path (due to interactions with the moving surface), the corresponding energy "blob" would be wider in the frequency domain. This has not been indicated here. The figure also shows a measured scattering function for the often-cited short-range, one-way path experiment in the Florida Strait.

2.2 Linear-Systems Approach

An alternative, but basically equivalent, approach to channel characterization is the linear-systems approach. Here, the medium is modelled as a "black box" with random characteristics and the input-output relations are studied. Making two basic assumptions about the medium enables one to arrive at a complete specification of the channel. In particular, it is assumed that the received contributions from differing paths (delay intervals) are statistically independent, and that the time-variant channel response (transfer function) is wide-sense stationary. Using the resulting so-called wide-sense stationary uncorrelated scattering (WSSUS) channel, an almost bewildering variety of correlation functions may be derived to characterize the channel (Bello <9>; Van Trees <10>). Naturally, the correlation functions are related to each other (through fourier transformation in one or more variables). As indicated, the "filter" modelling the acoustic medium must be a linear time-varying stochastic filter. In other words, the impulse response function, $h(t,\tau;\vec{r},\vec{r}_s)$, must account for spreading in time, frequency, and space. The observed field, $y(\vec{r},t)$, is then related to the source field, $X(\vec{r}_s, t-\tau)$, by the usual relationship, viz:

$$y(\vec{r},t) = \int h(t,\tau;\vec{r},\vec{r}_s)\, X(\vec{r}_s,t-\tau)\, d\tau$$

Stationarity in time is implicit in this expression.

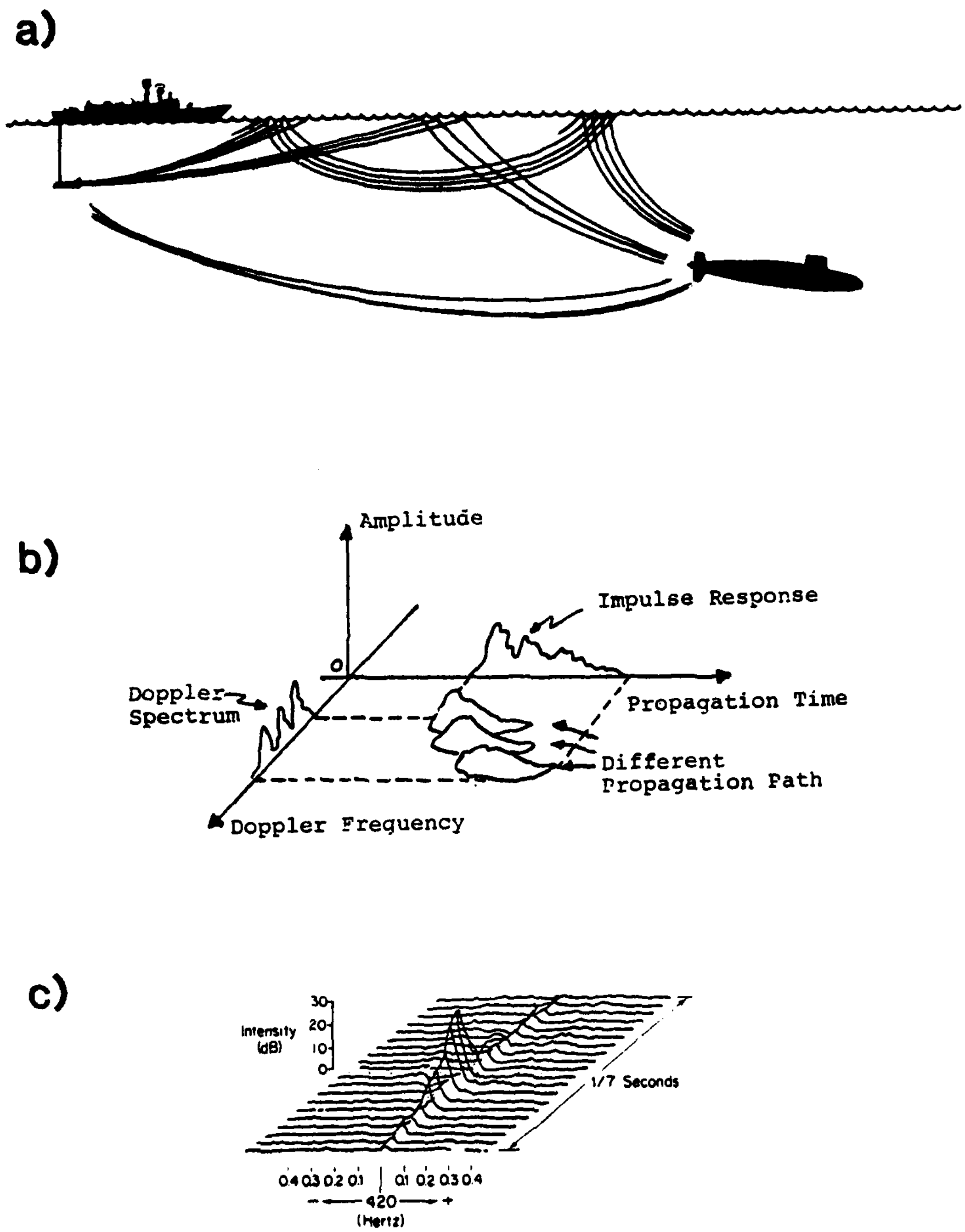


FIG. 4 SCATTERING FUNCTION (From <12>)

a) Three-path channel between surface ship and submarine.

b) Tri-modal scattering function.

c) Scattering function in typical summer conditions in the Florida Strait — sea-state 3 (from DeFerrari).

2.3 Caveats on the Use of Simple Methods of Channel Characterization

It is inappropriate, here, to dwell much longer on the subject of channel characterization; in any case, excellent references already exist <8,9,10,11>. Some additional comments, or caveats, are in order, however.

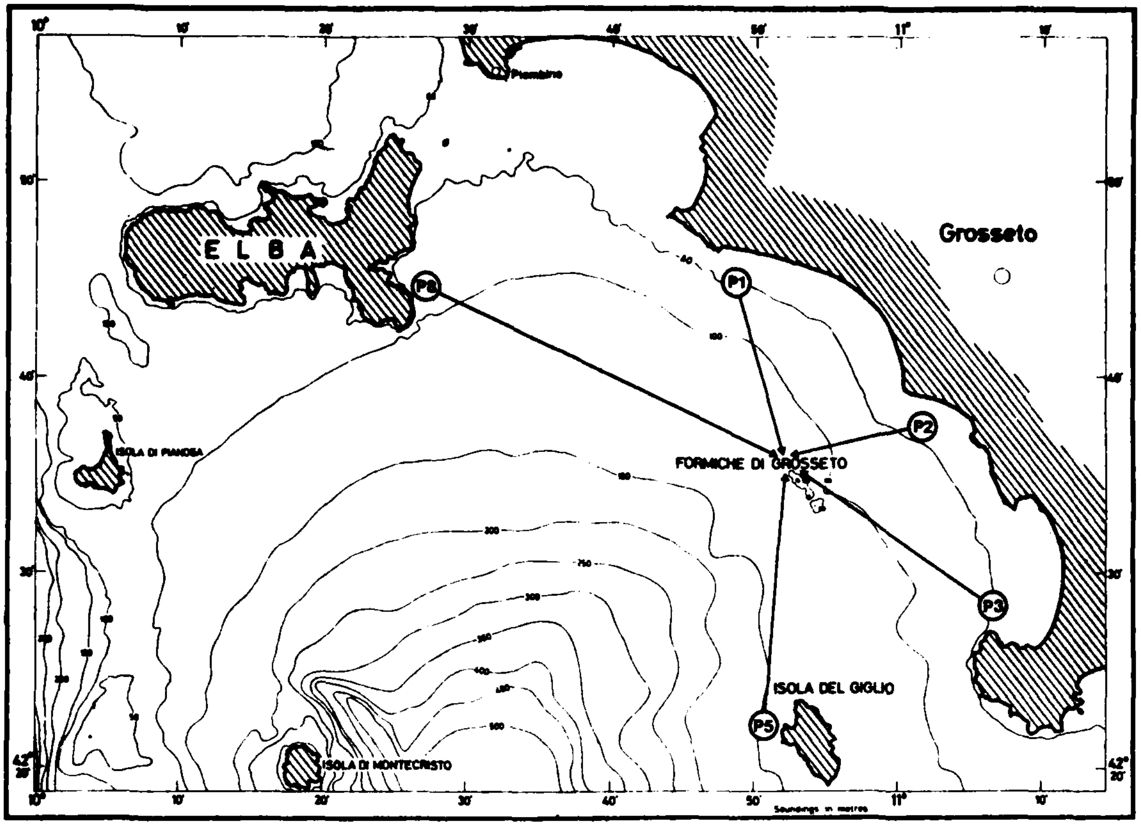
In principle, the measurement or calculation of the scattering function or the time-varying impulse response allows one to determine all the relevant parameters of the channel, and hence to design appropriate (optimum) receivers. In practice, however, one is confronted by the same formidable questions: what scattering function? which impulse response function? In other words, the assumption of stationarity - in either time, space, or frequency - is generally not valid. A measured impulse response, for example, is generally representative only of a very restricted set of environmental/experimental conditions. To paraphrase Heraclitus: "It is never possible to step twice into the same ocean".

One of the consequences of this is that the stationary model can be applied only to relatively short time intervals and narrow bands, resulting in a reduction in the precision of the estimates. Further, experimental conditions can sometimes rule out the meaningful use of the scattering function. An example of the latter is provided by the results of a series of experiments on acoustic transmission variability performed by SACLANTCEN and reported by Sevaldsen <13>. The experimental situation is depicted in Fig. 5. Linear fm pulses, and, in some cases, long-cw and pseudo-noise-modulated signals, in the frequency range of 1 to 6 kHz, were transmitted from transducers suspended from a ship anchored at each of several selected positions. The transducers were placed at several depths, including on the bottom. The receiver was a vertical array moored near the Formiche di Grosseto islands (Tyrrhenian Sea) and was considered to be fixed.

The spreading function (related to the scattering function) was calculated from the measured data and compared for two cases: one for the transducer fixed on the bottom, and the other for the transducer suspended above the bottom and hence able to move. Relative motions between source and receiver cause doppler shift and delay variations in the received signals. The delay variations show up not only as slow variations in arrival time but also as phase, and hence frequency, changes in the received signal. The results for these two cases are shown in Fig. 6a and 6b respectively. In the plots the arrival-time trend has been removed by aligning the matched-filter outputs following an averaged delay curve. The left parts of the figures show projections of the spreading function magnitude squared (SFMS) on the frequency axis while the right parts show projections of SFMS on the delay axis. The uppermost curves in both sets show projections of the scattering functions, i.e., the average of all the SFMSs below. The shifts in frequency between the spreading functions shown in Fig. 6a are attributed to fluctuations in the medium. The width in frequency of the scattering function is interpreted as the total bandwidth necessary to receive a narrow-band signal passed through the time-varying medium.

In Fig. 6b, the individual spreading functions are much narrower in frequency than the scattering function, suggesting that the variability of the medium has been masked by the movements of the source. Clearly, in this case, the scattering function is not very useful in describing the medium, since the shift in frequency width reflects the changing delay caused by source and/or receiver motion, rather than fluctuations in the medium. On the other hand, such a representation is useful in providing information on the effects of source/receiver motions.

a)



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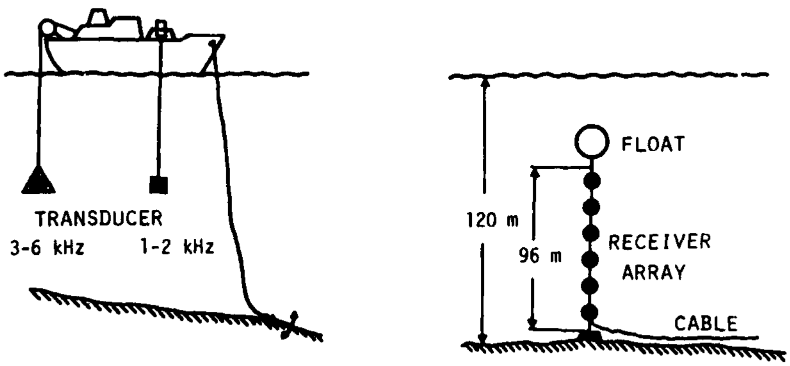


POSITION	RANGE	DEPTH	
		SUMMER	WINTER
1	16 300 m	67 m	68 m
2	12 800 m	58 m	56 m
3	22 100 m	60 m	54 m
5	25 300 m	70 m	124 m
8	38 500 m	80 m	65 m

FIG. 5 SACLANTCEN TRANSMISSION VARIABILITY EXPERIMENT (From <13>)
a) Map of the experimental area, showing transmitter positions.
b) Experimental situation.

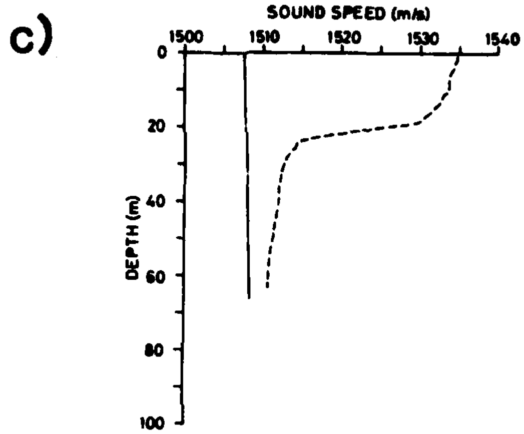


FIG. 5 SACLANTCEN TRANSMISSION VARIABILITY EXPERIMENT (From <13>)
c) Typical sound-speed profiles (summer and winter) measured in the area south of Elba.

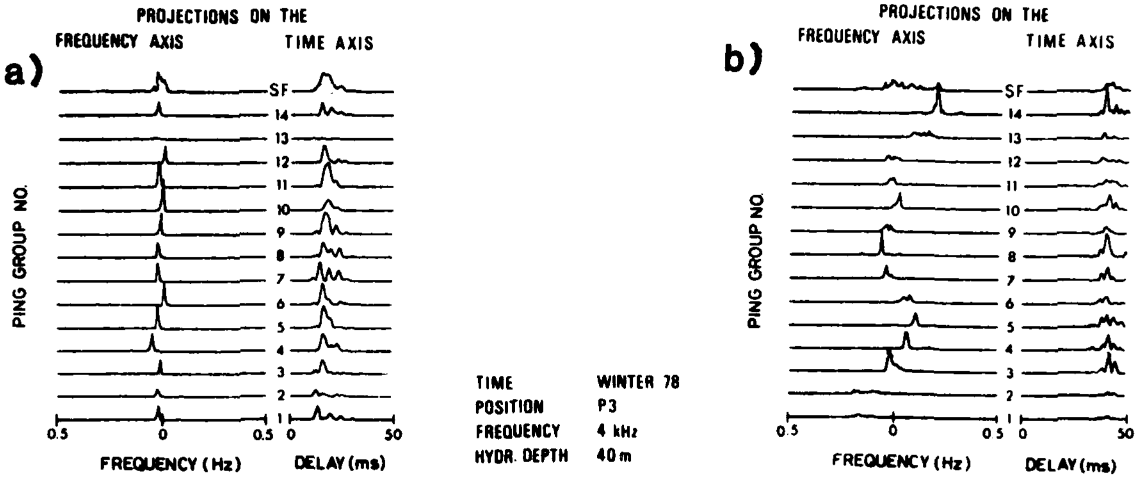


FIG. 6 EFFECT ON SPREADING FUNCTION OF RELATIVE MOVEMENTS (From <13>)
a) Transducer on the bottom.
b) Transducer suspended at 45 m.

2.4 Examples of Measured Time and Frequency Spreading of Acoustic Signals

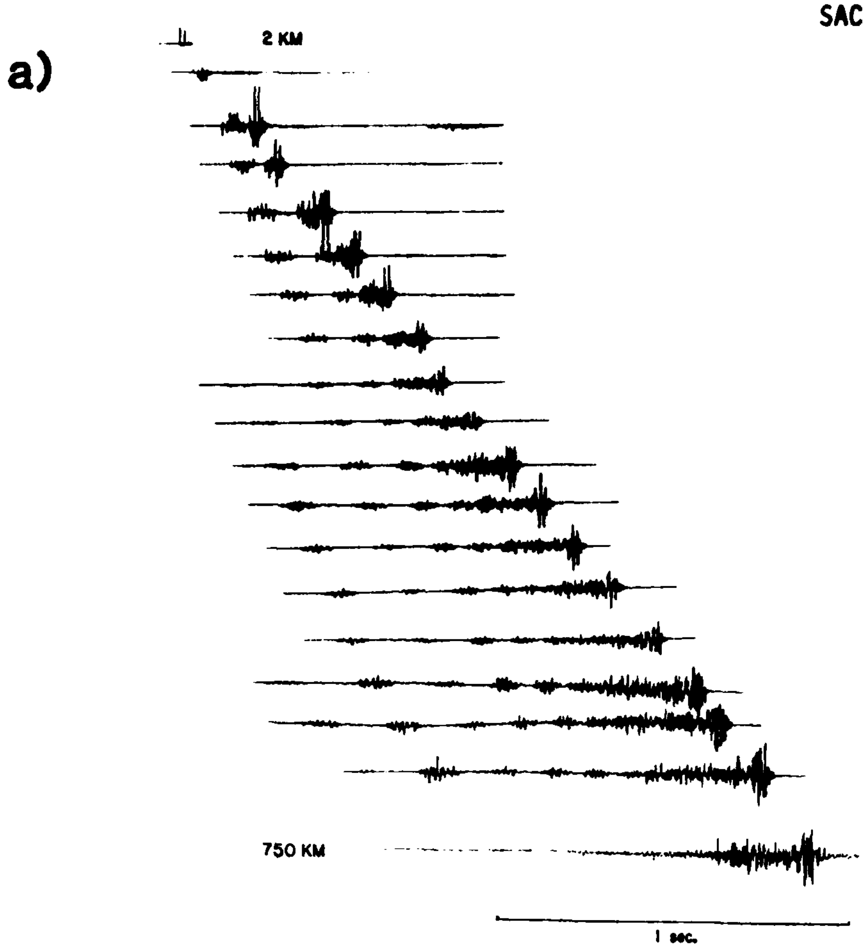
An example of medium-induced time stretching is presented in Fig. 7, which is based on data obtained in a 1982 SACLANTCEN experiment <14>. Figure 7a shows the time evolution of an explosive pulse (air-dropped SUS charge) in deep water over a range of 750 km. As seen, the impulse, which lasted a few milliseconds near the source, produced distant signals that persisted for a large fraction of a second. Figure 7b shows a similar result for shallow water. Here the pulse elongation occurs at shorter intervals than before, primarily as a result of greater boundary interactions of the signal. It is clear that such time stretching can distort information pulses by causing intersymbol interference, unless the interval between successive signals is made as long, or longer, than the multipath spread. In the particular case of Fig. 7a, in which the multipath spread is of the order of 1 s, the data rate necessary to avoid intersymbol interference is extremely low: about 1 pulse every second, i.e., a data rate of the order of 1 bit/s.

An example of surface-induced frequency spreading of a pure-tone signal is shown in Fig. 8 <15>. The originally pure tone acquires side-bands and is otherwise smeared in frequency. Apart from smearing the frequency of the signal, the sea surface also causes fluctuations in the signal's amplitude by imposing the wave spectrum on the carrier spectrum. This is shown in Fig. 9 <15>. The effect of the moving surface depends on its relative "roughness", measured in acoustic wavelengths, and on the grazing angle of the incident signal.

As a final example of measured spreading in frequency and time, reference is made to some experimental results reported by Ellinthorpe and Nuttal <16>. These experiments were conducted for one-way deep-water propagation paths in the western Atlantic over distances of from ten to several hundreds of miles. The source and receiver were either both fixed (fixed-fixed) or slowly moving. Multipath-induced time spreading was investigated by using narrow pulses of centre frequency near 5 kHz and pulse widths from 1 to 10 ms. With transducer beamwidths in the range of 1/10 to 1/3 radians, an impulse response duration, L, of 2 to 3 s was typically observed. At a resolution of 1 ms, 10 to 20 distinct arrivals were observed in the interval L. A pulse repetition interval of 5 s was used to avoid overlap between successive pulses.

Frequency shift spreading (i.e., B) was measured by transmitting sine waves in the 5 kHz centre-frequency region and calculating the spectral spreading from the envelope of the received signal. The procedure depends for its justification on a gaussian assumption that, the authors claim, was subsequently determined to be of doubtful legitimacy. Nevertheless, measured frequency spreads were typically about 1 Hz for slowly moving platforms; extremes as high as 5 Hz and as low as the experiment's limit of resolution, 0.1 Hz, were also encountered.

Coupling the values of B and L, the typical BL product at 5 kHz is two to three; i.e. at this centre frequency the channel is typically overspread. Since frequency spreading is essentially a doppler-induced phenomena, and should therefore decrease with decreasing centre frequency, it may be possible for an overspread channel to behave like an underspread channel at lower frequencies. With this in mind, measurements were made over a range of frequencies extending into the low hundreds of hertz. The results confirmed that the width of the frequency smear did decrease with centre frequency, following an approximately linear relationship down to about 500 Hz where it abruptly drops by an order of magnitude or more. A fixed-fixed reference path of only ½ mile in length, which did not intercept the surface, revealed no frequency smear up to 1 kHz, the highest frequency transmitted over it. This behaviour is believed to reflect the dominant role played by the surface of the ocean in paths considered for the Ellinthorpe experiment. In particular, one of the features of the statistics of wind-generated surface waves is the abrupt vanishing of the spectrum at low frequencies. In any case, at the lower frequencies the ocean did offer a channel that was underspread, and hence increased the possibility of its reliable exploitation.



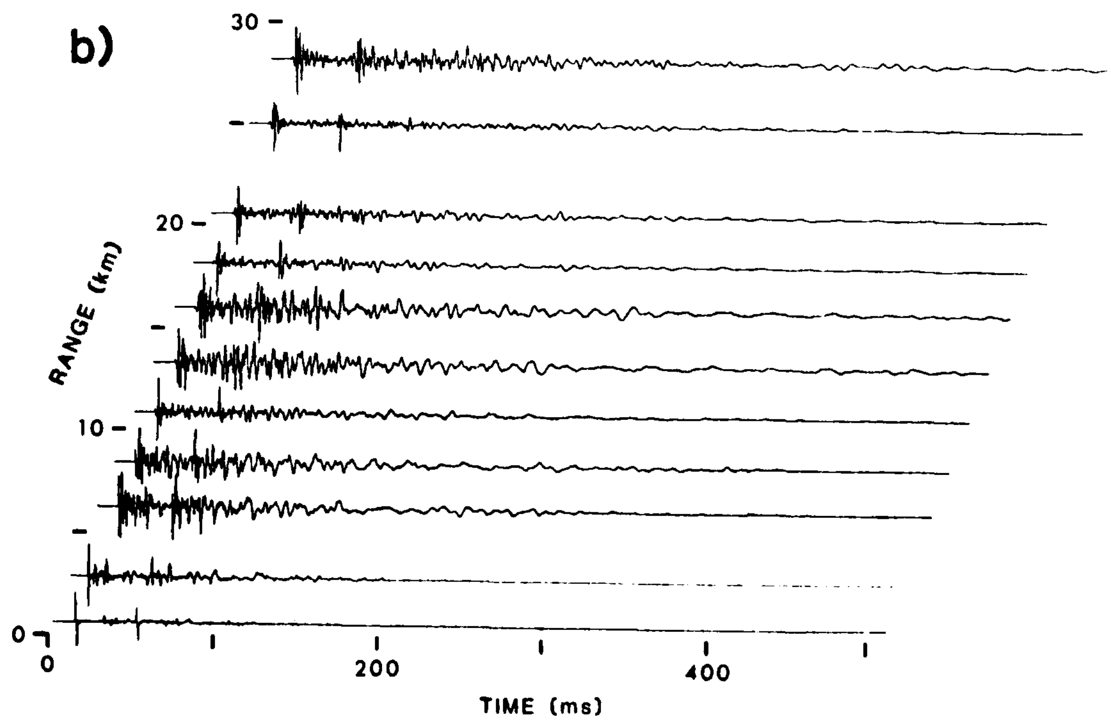


FIG. 7 TIME SPREAD OF AN EXPLOSIVE PULSE, OBTAINED FROM A RECENT SACLANTCEN EXPERIMENT (From <14>)
a) Deep water.
b) Shallow water.

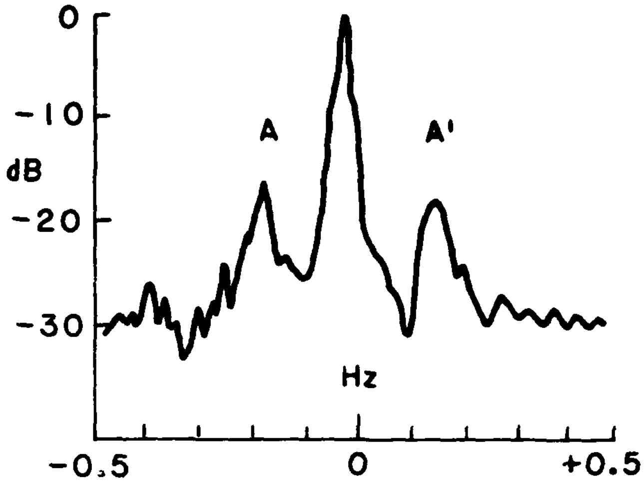


FIG. 8 FREQUENCY SPREAD OF FORWARD-SCATTERED PULSES (From <15>)
Frequency spread of forward-scattered 100 ms 1702 Hz pulses over a distance of 19 mi in shallow water; analysis band 0.01 Hz. USN Underwater Systems Center data.

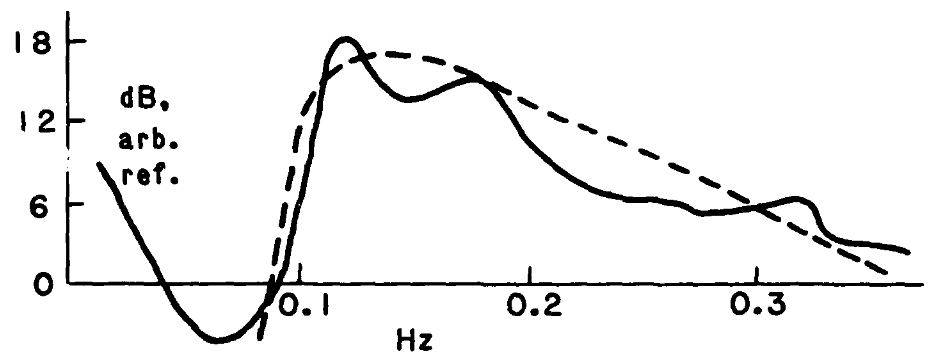


FIG. 9 MODULATION SPECTRUM OF A SURFACE-REFLECTED SIGNAL (From <15>)
Modulation spectrum of the envelope from a 275 Hz cw source towed at 2.7 kn at a range of 23 mi. Dashed line is Neuman-Pierson wave spectrum for a wind speed of 20 kn. Analysis bandwidth 0.02 Hz.

3 THE EFFECTS OF ACOUSTIC VARIABILITY ON SONAR PERFORMANCE

Several consequences of signal degradation have been mentioned in the preceding chapter, sometimes in passing. It may be useful to summarize these and other similar observations.

Generally speaking, the degradations in sonar performance are a result either of loss in spatial/temporal coherence of the acoustic signal or of noise-like fluctuations in the signal amplitude.

The loss of frequency coherence due to time-spreading of a transmitted signal, arising, for example, from multipath propagation, tends to lead to information loss from "intersymbol interference". The resulting uncertainty in amplitude and/or arrival time can lead to errors in range estimation. For discrete multipath arrivals, the arrivals can be separated if the transmission frequency bandwidth is large enough. Similarly, temporal decorrelation, caused by frequency spreading, leads to the requirement of larger frequency bandwidth and limits the length over which useful coherent integrations may be performed.

The loss of spatial coherence has analogous effects. Uncertainty in the apparent bearing (angular location) of a source – i.e., angular spread – is measured by the reciprocal of the distance over which the received signals are correlated (coherence length). Hence the ability of a receiving array to discriminate either noise or reverberation against an omnidirectional source is limited by the degree of spatial decorrelation. The gain of an array is also limited by the degree of spatial decorrelation of the signal across the array.

As a final comment on the effect of signal fluctuations on sonar performance, reference is made to Fig. 10 <3>. This shows plots of

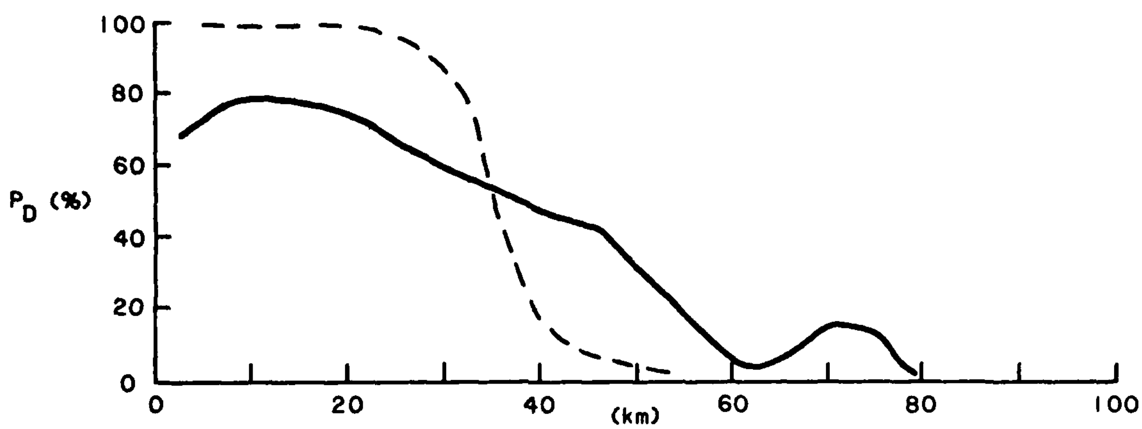


FIG. 10 THE EFFECT OF FLUCTUATIONS ON DETECTION PROBABILITY (From <3>) Detection probability P_D as a function of range as calculated (dashed curve) and as observed in a field exercise (solid curve).

detection probability, P(D), as a function of range and indicates the effect of signal/noise fluctuations. In particular, the dashed curve represents the "ideal" case, calculated using standard receiver operating characteristic (ROC) curves that assume a steady signal and ignore fluctuations; the solid curve shows what was actually observed during a naval exercise with a passive sonar.

The performance difference indicated in Fig. 10 is quite reasonable, since it suggests behaviour that is quite plausible. In particular, targets tend to be detected at ranges longer than expected during periods of signal surges and lost at unexpectedly short ranges during periods of signal fades. The net effect, then, is to cause the actual detection probability to fall off more slowly than theory would predict.

4 ACOUSTIC VARIABILITIES CAUSED BY THE ENVIRONMENT

The literature on environmental and acoustic variability in the ocean is vast, if not overwhelming. For the purpose of this brief survey, however, it will suffice to give a few selected examples of typical observations. Wherever possible, environmental variability will be correlated with observed variability in one or more of the acoustic parameters (amplitude, phase, transmission loss).

4.1 Temporal and Spatial Scales of Ocean Variability

To place environmental variations in perspective it is useful to consider, briefly, the temporal and spatial scales characterizing ocean variability. Oceanic conditions can be broken down into mean and fluctuating components in several ways. A useful approach for underwater acoustics is that used by De Santo <17>, Dugan <5>, and others. In particular, ocean conditions are considered to consist of:

a) A mean vertical sound-speed profile that represents local climatology.

b) A mesoscale component that is deterministic on the acoustic time scale.

c) A statistical component that represents smaller fluctuations due to internal waves and fine structure and must be considered random in some sense on the acoustic time scale.

The sound speed is correspondingly modelled as

$$C(\vec{X},t) = C_0(Z) + C_1(\vec{X}) + C_2(\vec{X},t),$$

where

$C_0(Z)$ is the deterministic refractive term,

$C_1(\vec{X})$ is a sound-speed correction due to mesoscale phenomena, modelled deterministically,

$C_2(\vec{X},t)$ is the random component.

The approximate size scales are $C_0 \cong 1500$ m/s, C_1 is smaller than C_0 by a factor of 10^{-2}, and C_2 is smaller than C_0 by a factor of 10^{-4}.

To the above list it is tempting to add tidal phenomena as a fourth item, or perhaps even to include it under mesoscale phenomena. However, this is not generally done in the literature, since these phenomena seem to form a class by themselves. In keeping with this tendency, tidal-induced variability will also be treated separately in this memorandum (Sect. 4.2).

4.1.1 Ocean Climatology

The ocean climatology, or, as it was formerly called, the general circulation, exhibits the largest horizontal scale of variability in the ocean, limited only by the size of the basin. The long-term mean vertical profile is depth dependent and seasonally variable in the upper few hundred metres. In the deeper parts of the ocean, the variables, "when viewed in the proper parameter space" <5>, have not varied measurably through this last century of accurate measurements. This mean structure represents a long-term balance between locations and times at which water of particular characteristics is formed and those at which it is destroyed. An example of the spatial variation of temperature is given in Fig. 11 <18>, which shows the existing temperature distribution for a north-south section of the Atlantic Ocean. As seen, the deep layer extends to the surface in the polar regions. Another example of spatial temperature variations, obtained with a towed thermistor chain, is shown in Fig. 12 <4>. Here the region between 25.8°N and 27.5°N contains a cold front, perhaps an eddy; the region between 27.5°N and 28.3°N shows an oceanic front, probably the northern boundary of the Kuroshio current (discussed later). Since a change in temperature of 1°C roughly corresponds to a change in sound speed of 3.6 m/s, it is clear that the sound-speed profile varies considerably along such a track. The shift in depth of the main thermocline is again evident. The latter effect is summarized in Fig. 13 <19>. An example of a deep ocean sound-speed profile is shown in Fig. 14 <2>. This represents an average profile and its extremes, obtained from Nansen casts taken over a 9-year period at a location 15 n.mi southeast of Bermuda. A typical diurnal variation of temperature in the surface layer is shown in Fig. 15 <20>. The effect of latitude on sound speed is indicated in Fig. 16 <19>; not surprisingly, the trends shown are similar to those shown for the effect of latitude on water temperature.

Figure 17 <5> gives an example of historical (i.e., temporal) variability of temperature and salinity in a small area of the subtropical northwest Pacific in October and November. The data were accumulated over many years by bottle samples from research vessels and ocean weather stations. Although some of the scatter may be due to spatial variability, much of it is due to temporal variability, since many years of data are shown. If a scatter plot were made of the sound speed, it would vary by as much as 30 m/s even at 500 m depth, mostly due to the temperature variability.

The third plot in Fig. 17 shows the power of temperature-salinity (T-S) plots in ordering the data. From such plots one can identify different water types and say something about the type of mixing that has occurred. The details can be found in <5>.

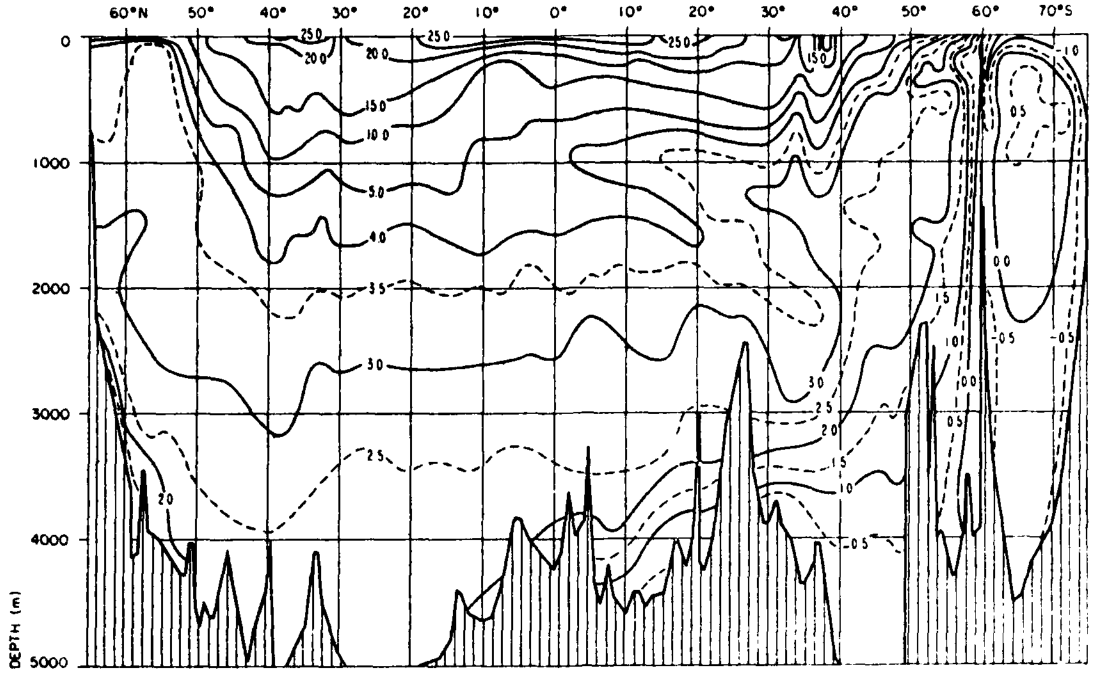


FIG. 11 A NORTH-SOUTH TEMPERATURE SECTION OF THE ATLANTIC OCEAN (From <18>)

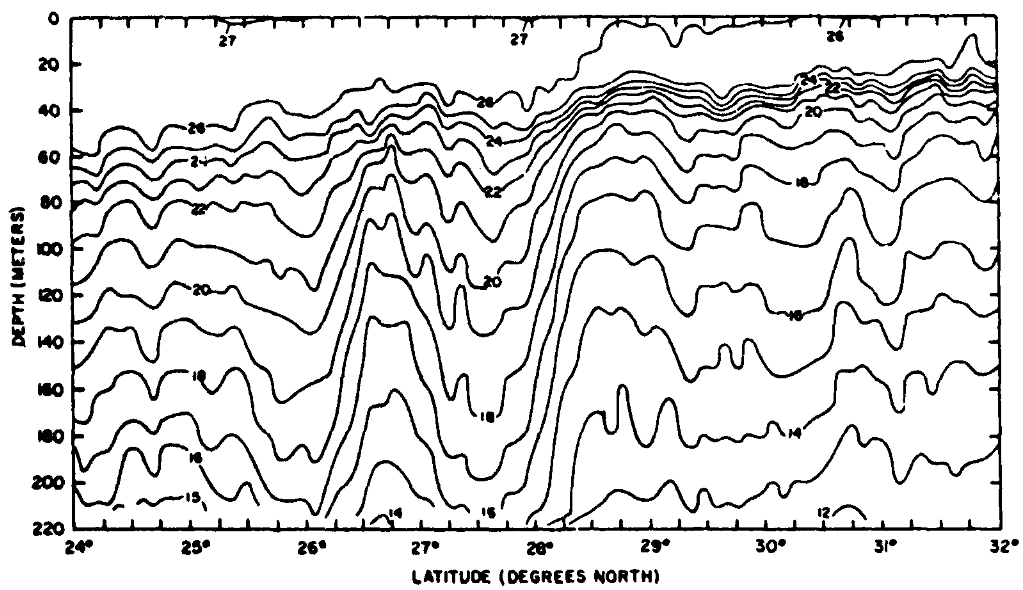


FIG. 12 EXAMPLE OF THE SPATIAL VARIATION OF OCEAN SURFACE TEMPERATURE (From <4>) The thermal structure (°C) of the surface layer of the Pacific Ocean as measured with a thermistor chain shows a cold dome between 26°N and 27°N and an oceanic front at 28°N in the area of subtropical convergence.

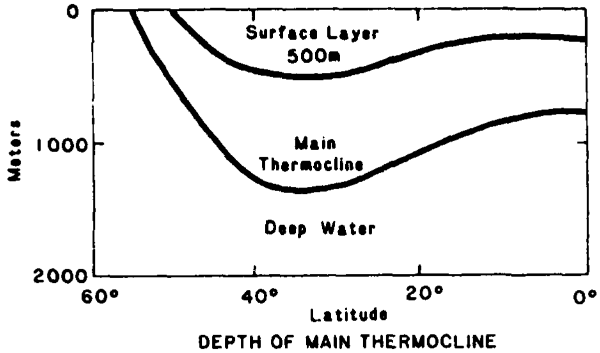


FIG. 13
THE DEPTH OF THE MAIN THERMOCLINE AS A FUNCTION OF LATITUDE (From <19>)

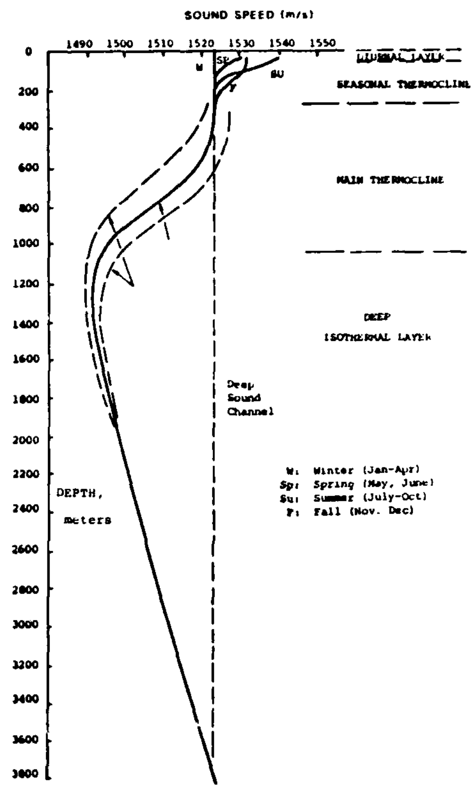


FIG. 14
DEEP OCEAN SOUND-SPEED PROFILE (From <2>)
Based on Nansen casts taken every two weeks over a 9-year period at a location 15 mi SE of Bermuda.

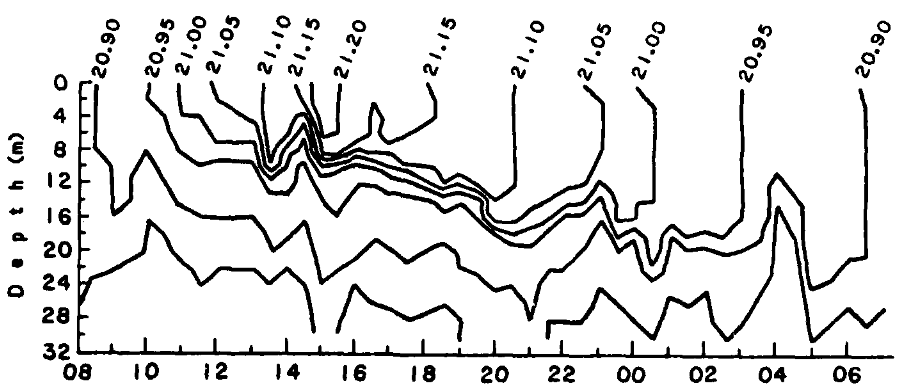


FIG. 15 TYPICAL DIURNAL VARIATION OF OCEAN SURFACE TEMPERATURE (From <20>)
Diurnal warming of the upper ocean (according to Howe and Tait). The isotherms (°C) were plotted from measurements made at 30 min intervals on 23-24 July 1966.

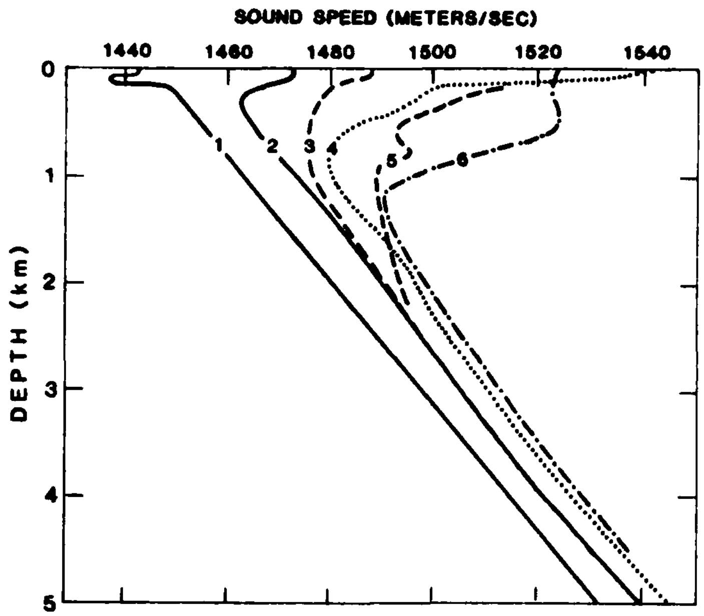


FIG. 16 THE EFFECT OF LATITUDE ON SOUND SPEED (From <19>)
(1) Antarctic water south of 60°S
(2),(3) North Pacific Ocean between 45° and 55°N
(4) North Pacific south of 30°N
(5) Indian Ocean — waters influenced by Red Sea
(6) Atlantic Ocean, 40°N

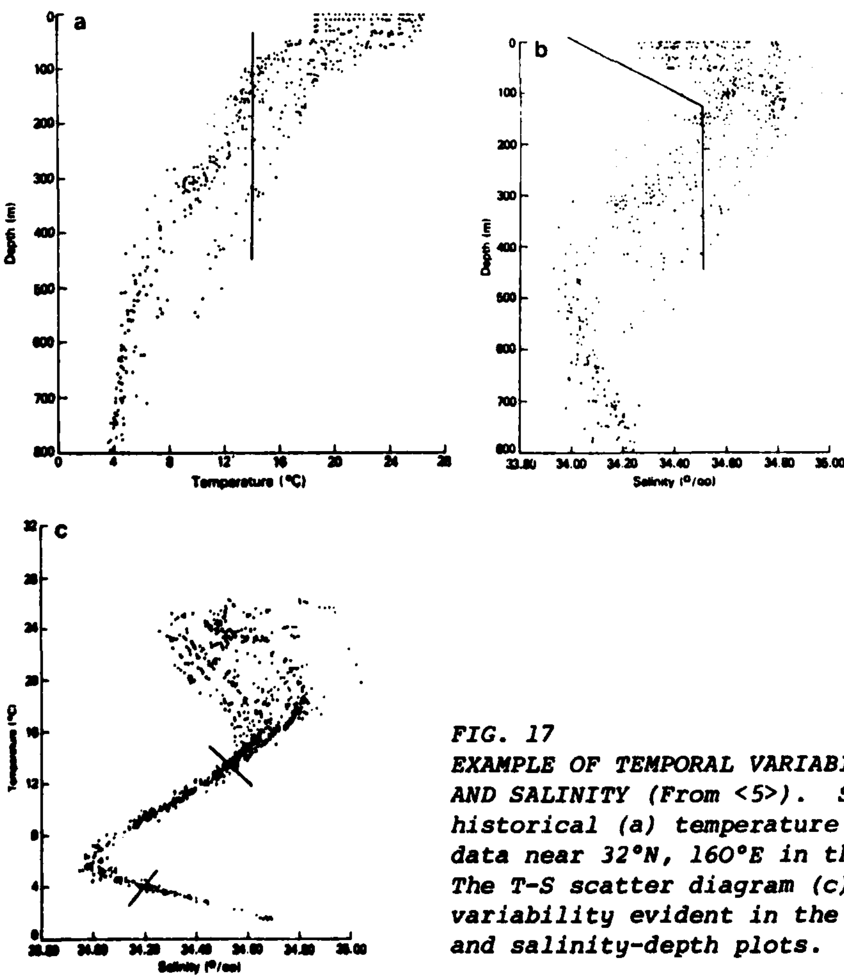


FIG. 17
EXAMPLE OF TEMPORAL VARIABILITY OF TEMPERATURE AND SALINITY (From <5>). Scatter plots of historical (a) temperature and (b) salinity data near 32°N, 160°E in the North Pacific. The T-S scatter diagram (c) reduces the variability evident in the temperature-depth and salinity-depth plots.

Another example in this category is given in Fig. 18 <21>, which shows the effects of seasonal changes on acoustic propagation. The figure shows isoloss transmission contours in the frequency/range plane for an acoustic run made over the same track under summer (top curve) and winter (bottom curve) conditions. It is seen that for a given combination of propagation range and frequency the corresponding transmission loss is higher in summer than in winter. Since the data shown were obtained in shallow water the higher summer losses reflect the interaction with the sea-floor of the downward-refracted rays.

The effects of seasonal changes on the phase of cw acoustic signals have been clearly demonstrated by Weston et al <22> in propagation measurements in shallow coastal waters off the British Isles. In particular, the phase delay was shown to vary with season, being least in summer, and to change by as much as 3 rad per day per km. It was found that these seasonal trends could be observed even over comparatively short periods, a few days for example. The results are not unexpected: phase delay, which is determined by the number of acoustic wavelengths between two fixed transducers, will be least (greatest) when the sound speed is greatest (least). Since speed of sound in sea water increases with temperature, the observed trends are quite plausible. Nevertheless, these extremely useful observations had not, according to the authors, been made prior to their measurements. An example of these results is given in Fig. 19 <22>, which shows measured phase delay over a 5½ day period of an approximately 2 kHz signal propagated over a 7.8 km path. It is clear that, even for this short period, one detects a long-term trend; namely, a sweeping increase in phase delay due to the fact that the measurements were made in January 1964, while the water was still cooling. The predicted seasonal phase delay agrees quite well with the measurements, if one considers that the prediction is based on temperature measurements at the right season but the wrong year. In Fig. 19 the tidal oscillations are superimposed on the seasonal trend; these are discussed in Sect. 4.2. As a final comment on the results of Weston et al, it is noted that seasonal trends in phase delay were demonstrated unequivocally only for short-range propagations. For longer ranges (e.g., 137 km) consistent seasonal trends were not observed, no doubt due to the ambiguities inherent in low signal/noise ratio signals.

4.1.2 Mesoscale Variations

Mesoscale fluctuations lie between the large-scale general circulation and the smaller scale internal waves, etc. Their spatial scales are of 50 to 500 km in the horizontal and of up to the ocean depth in the vertical; their temporal scales are of the order of many days to months. They are characterized by fronts and eddies and, because of analogies with atmospheric fronts and highs and lows, mesoscale fluctuations are referred to as the ocean weather system. Since these features can generally be tracked for days or even months at a time, they can be considered to be deterministic perturbations, albeit large ones, from the mean structure. The basic building blocks of mesoscale fluctuations are said to be planetary (Rossby) waves <5>.

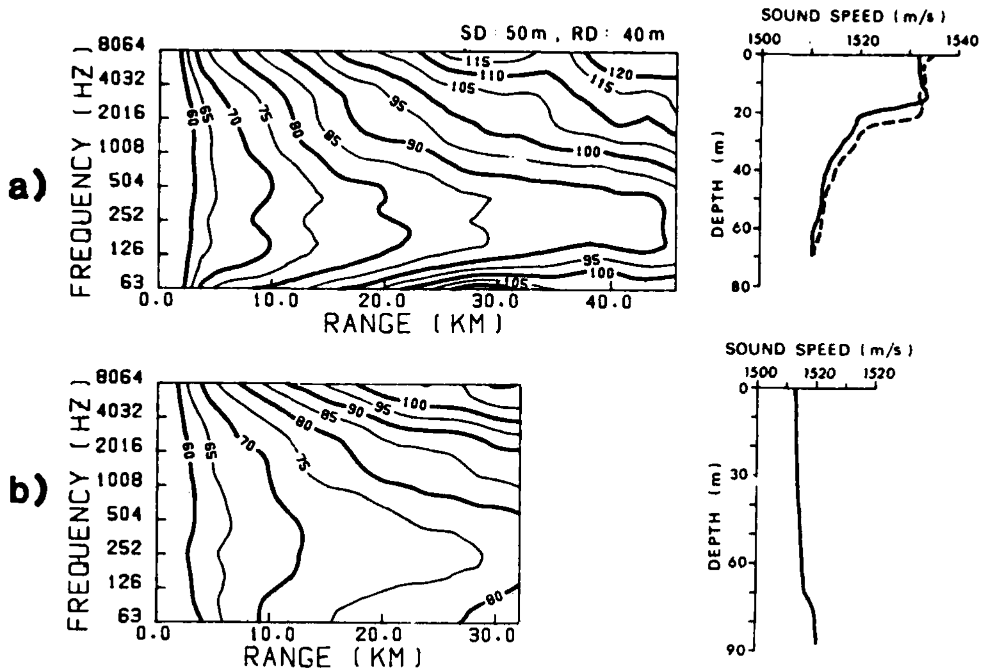


FIG. 18 EFFECT OF SEASONAL CHANGES ON ACOUSTIC PROPAGATION (From <21>)
Isoloss transmission contours in frequency/range plane in the same area in a) summer and b) winter

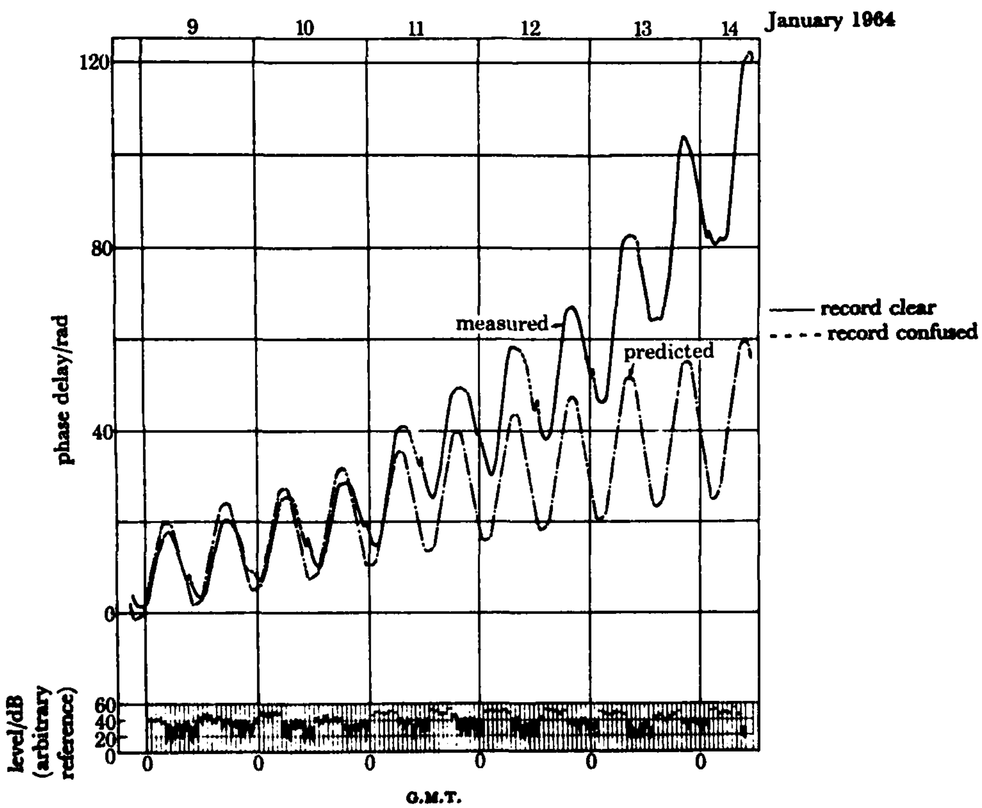


FIG. 19 EFFECT OF SEASONAL CHANGES ON THE PROPAGATION OF A CW ACOUSTIC SIGNAL (From <22>)
January 1964 fluctuations: measured and predicted phase curves and recorded amplitude samples (2083.3 Hz, 7.8 km, 047°).
1 min samples taken each hour for amplitude record.

Ocean fronts occur at the boundaries of different ocean water masses, and are often associated with major ocean current systems. For example, the Kuroshio front in the northwestern Pacific defines the northern boundary of the warm Kuroshio current (the Pacific analogue of the Gulf Stream), and the Oyashio front defines the southern boundary of the cold Oyashio current (the region between these two fronts is termed the subarctic-subtropical transition zone). These fronts are amongst those shown in Fig. 20 <18>. Figure 21 presents the vertical (a) temperature and (b) and (c) sound-speed sections through these fronts in February 1976 <4>.

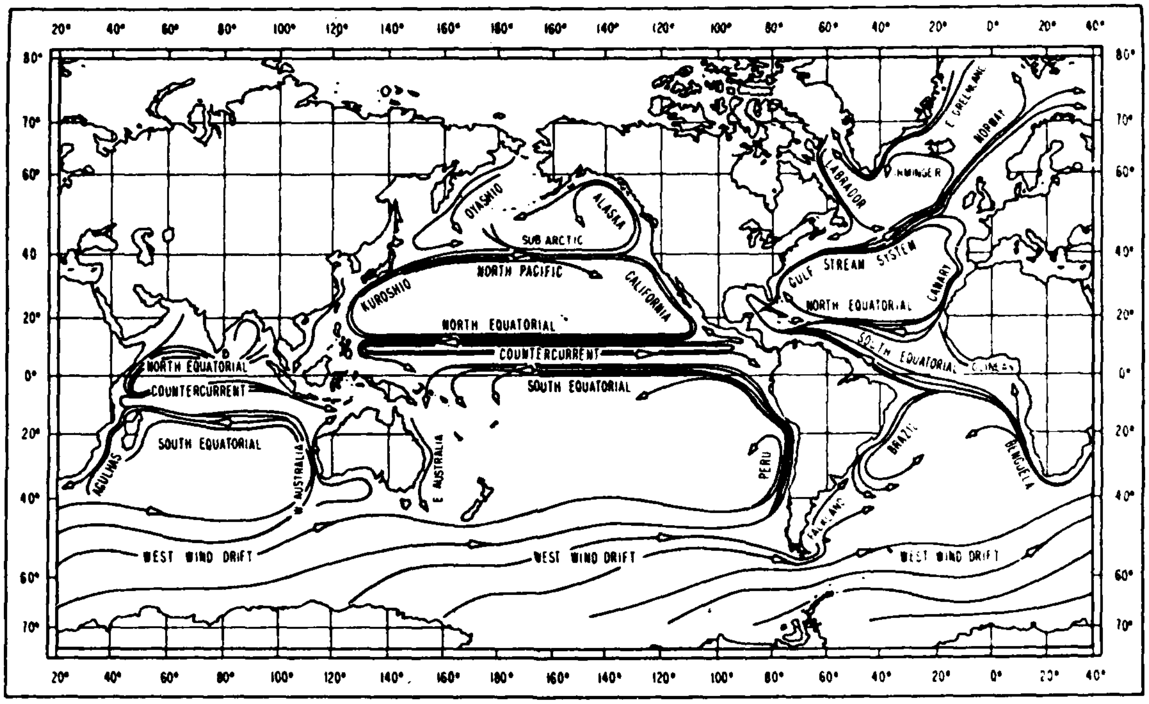


FIG. 20 AVERAGE SURFACE CURRENTS OF THE WORLD'S OCEANS (From <18>)

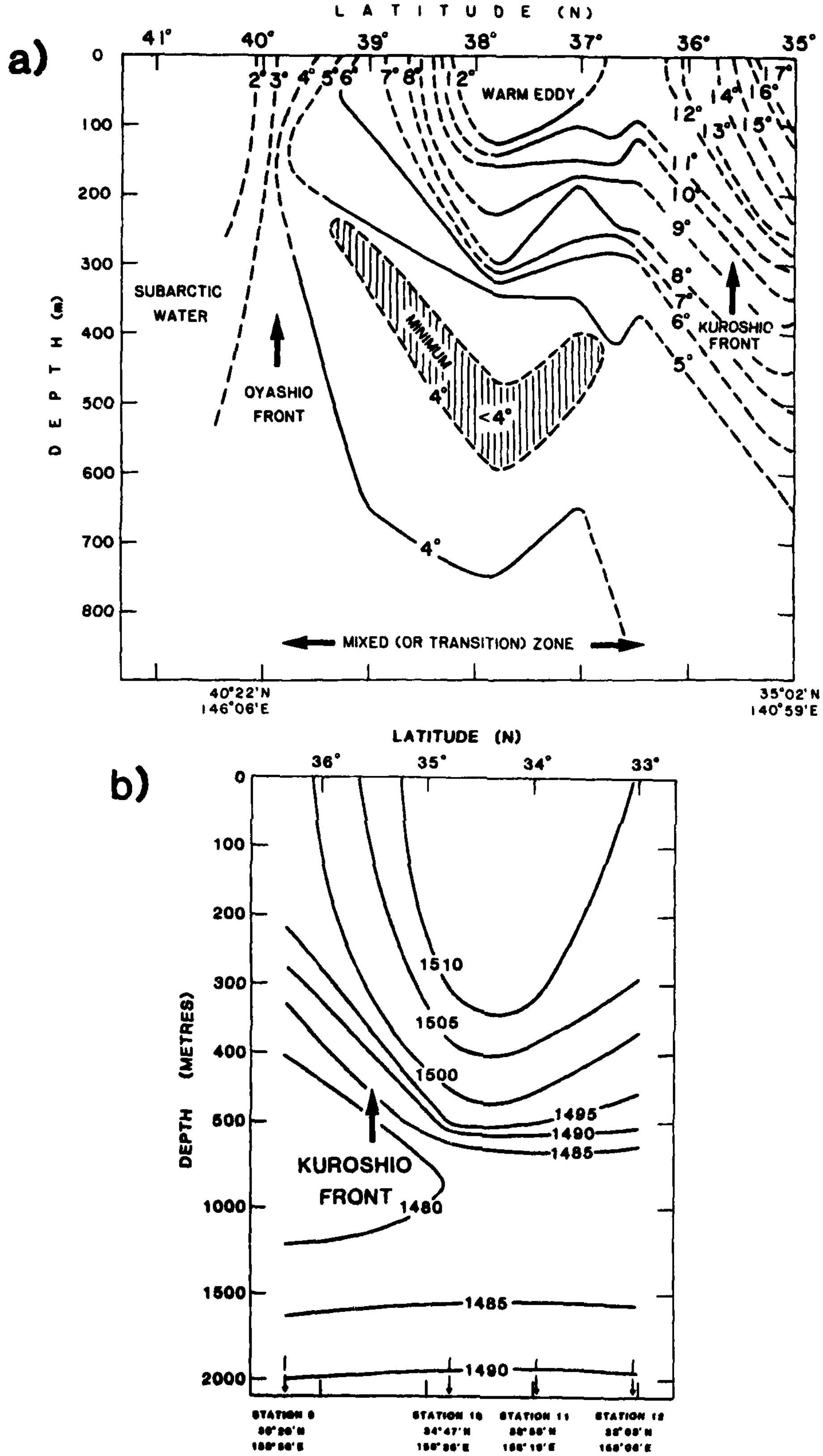


FIG. 21 VERTICAL DISTRIBUTIONS THROUGH THE OYASHIO AND KUROSHIO FRONTS (From <4>)
a) Vertical distribution of temperature between 35°02'N, 149°59'E, and 40°22'N, 146°06'E. 6-8 February 1976.
b) Vertical distribution of sound speed between 36°20'N, 158°56'E, and 33°03'N, 158°08'E. 14-15 February 1976.

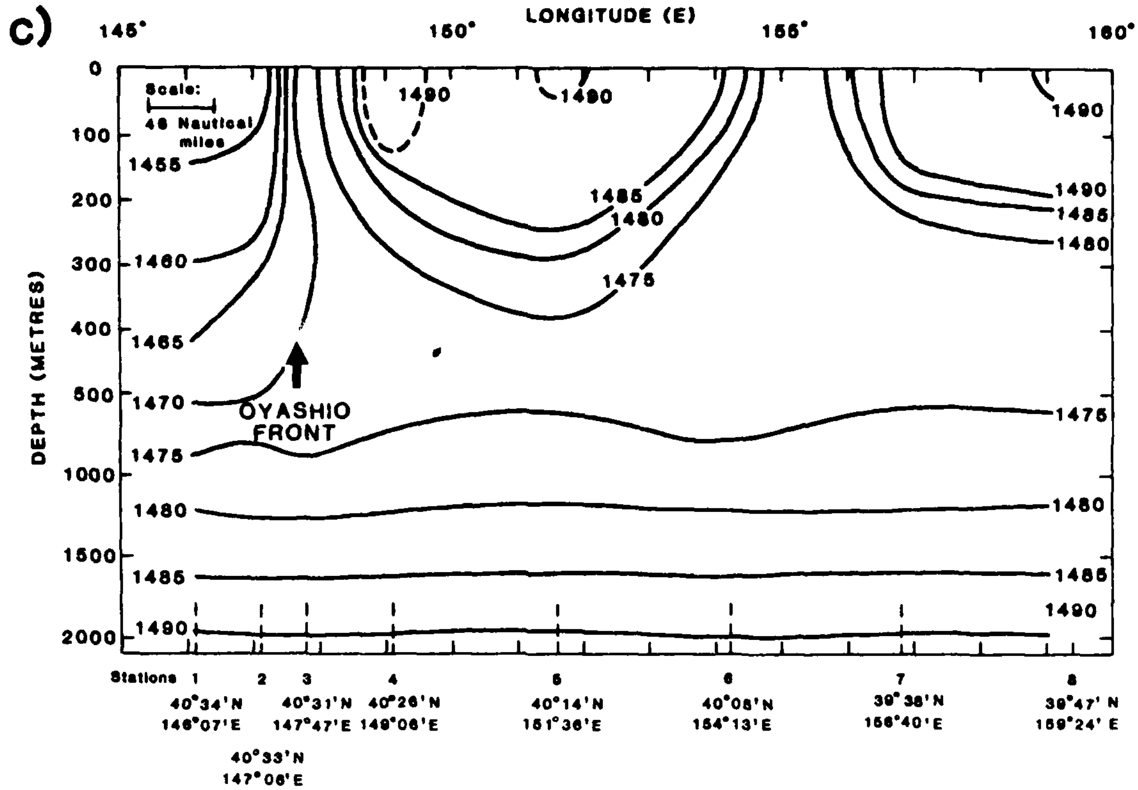
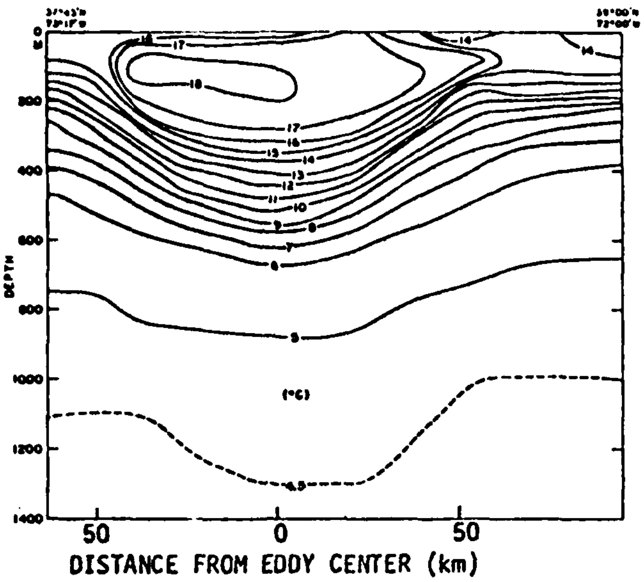


FIG. 21 VERTICAL DISTRIBUTIONS THROUGH THE OYASHIO AND KUROSHIO FRONTS (From <4>)
c) Vertical distribution of sound speed between 40°34'N, 146°07'E, and 39°47'N, 159°24'E. 8-11 February 1976.

Ocean current systems are important acoustically not only for their effects on sound transmission, but also because of the role they play in generating ocean eddies. Eddies are generated when large meanders of an ocean current "pinch off" to form vortex-like ocean structures that rotate about a core. For example, meanders to the south and east of the Gulf Stream entrain cold slope water and develop a counter-clockwise (cyclonic) circulation about a cold core; meanders to the north and west entrain warm water from the Sargasso sea and develop a clockwise (anticyclonic) rotation about a warm core. Both warm and cold eddies tend to drift to the south or southwest with a speed of a kilometre or so per day, and often rejoin the Gulf Stream. They are important because they contain an appreciable fraction of the kinetic energy in the body of the ocean, because of their roles in ocean-mixing processes and in returning energy to the Gulf Stream, and, as with fronts, for their influence on sound propagation. Figure 22 presents vertical a) temperature, b) salinity, c) sound speed, and d) current sections for cyclonic and anticyclonic eddies generated by the Gulf Stream <4>.

a)

ANTICYCLONIC
EDDY



CYCLONIC
EDDY

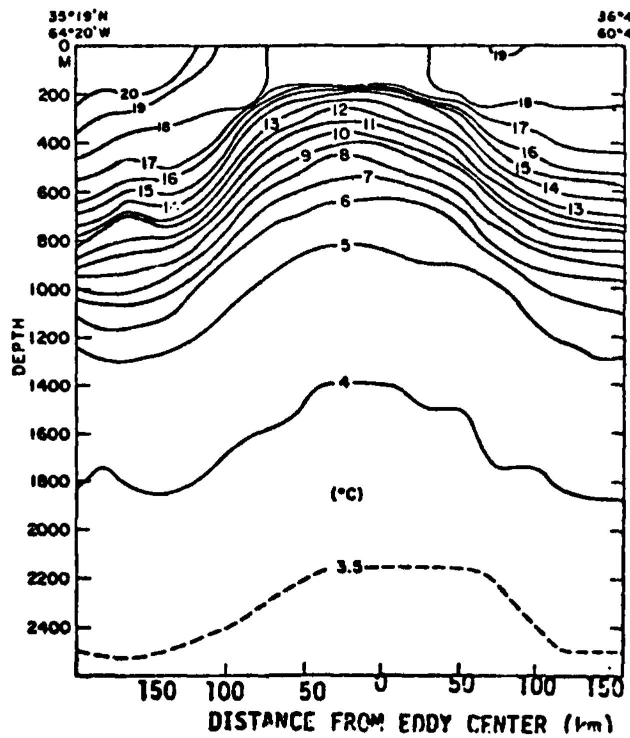


FIG. 22 VERTICAL SECTIONS THROUGH CYCLONIC AND ANTICYCLONIC GULF STREAM EDDIES (From <4>)
a) Temperature sections.

b)

ANTICYCLONIC EDDY

CYCLONIC EDDY

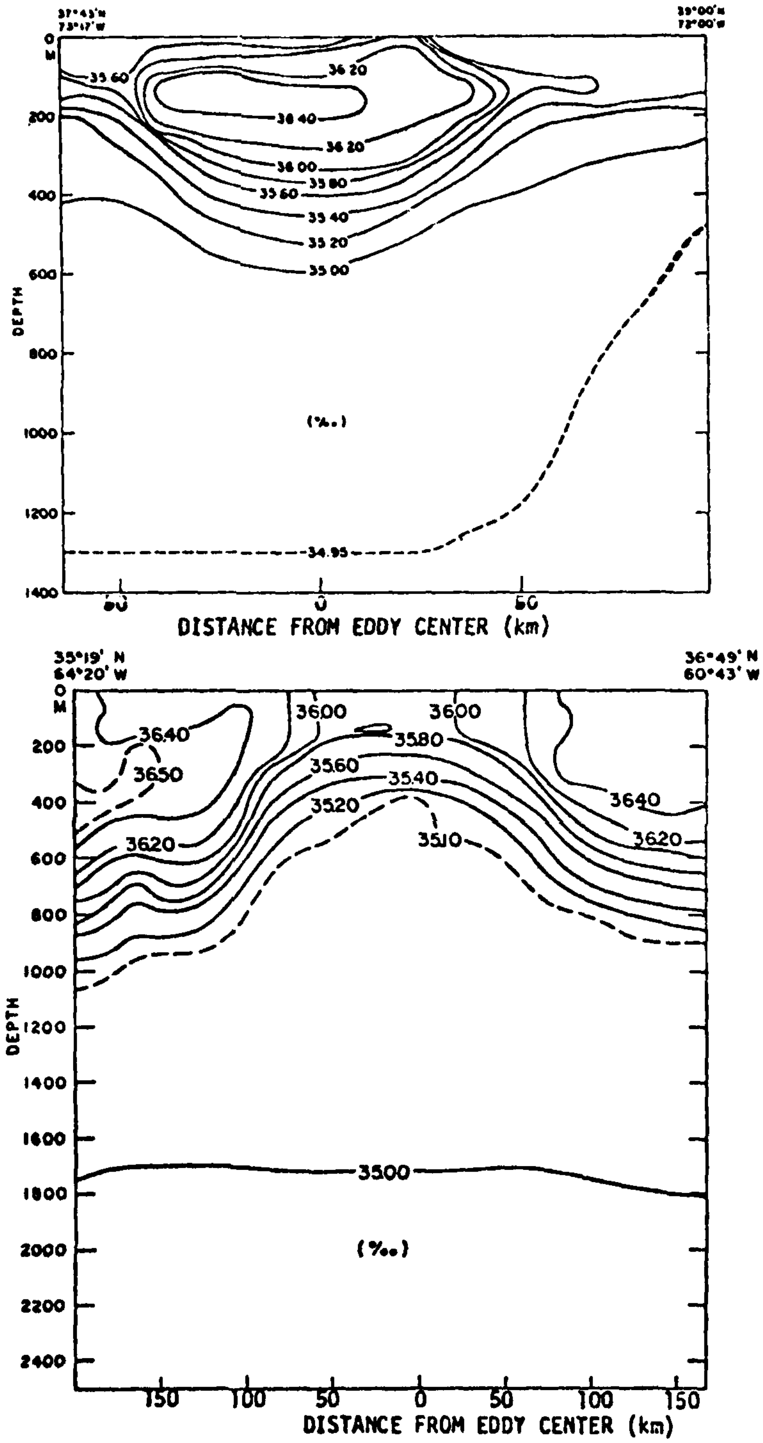


FIG. 22 VERTICAL SECTIONS THROUGH CYCLONIC AND ANTICYCLONIC GULF STREAM EDDIES (From <4>)
b) Salinity sections.

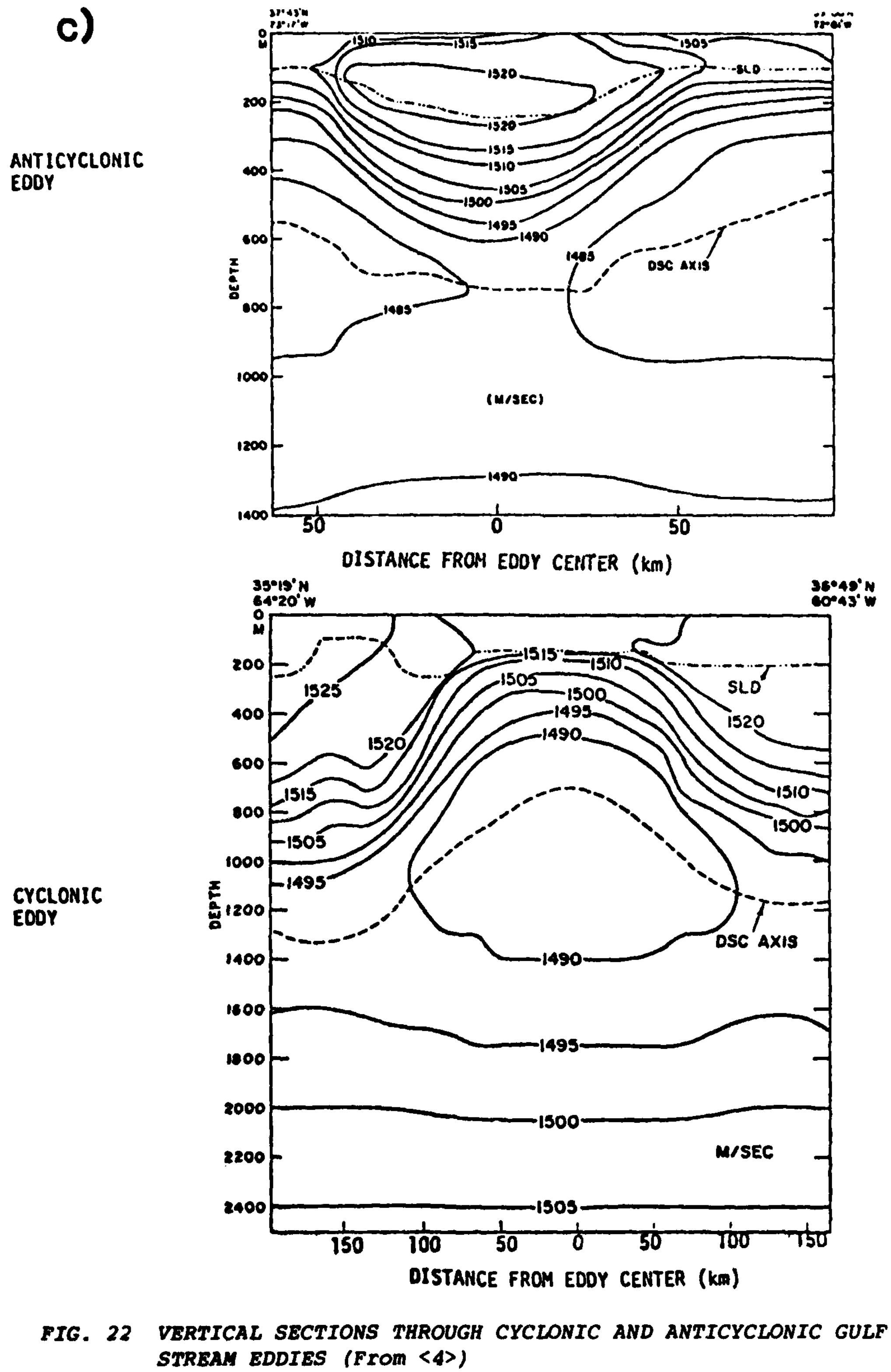


FIG. 22 VERTICAL SECTIONS THROUGH CYCLONIC AND ANTICYCLONIC GULF STREAM EDDIES (From <4>)
c) Sound-speed sections.

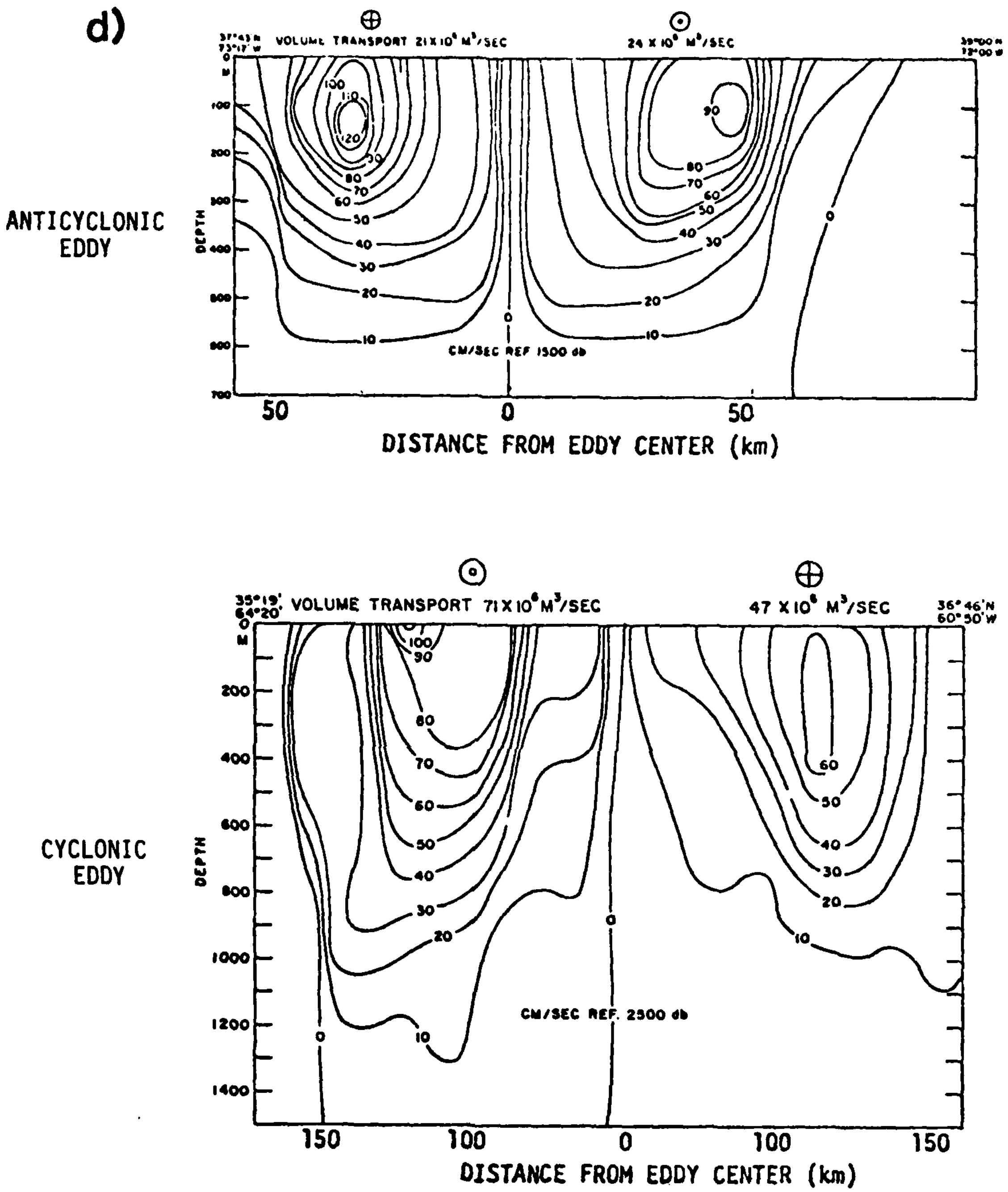


FIG. 22 VERTICAL SECTIONS THROUGH CYCLONIC AND ANTICYCLONIC GULF STREAM EDDIES (From <4>)
d) Current section and transport.

From these data it is evident that eddies can have significant effects on sound propagation, warm eddies tending to increase both the depth of the sound speed maximum above the deep sound channel (often termed the sonic layer depth), and the depth of the axis of the deep sound channel itself, while cold eddies tend to have the opposite effects.

When an eddy crosses a transmission path, the intensity of the received sound may change by as much as a factor of 10 <23, 24>. Moreover, the existence of currents and current shear causes changes in the travel time and pulse shape for signals travelling up current or down current. In general, the larger scale processes such as mesoscale eddies and fronts, tides, major current systems, etc. do not scatter the sound, but modulate the rays, giving rise to slow travel-time variations <23, 24>.

Boundaries of large-scale currents, such as the Gulf Stream and the Kuroshio, represent frontal zones separating water masses with essentially different physical characteristics. Within these frontal zones, temperature, salinity, density, and sound-speed suffer strong variations. For example, at the northern boundary of the Gulf Stream (north of 35°N) the temperature drop is 10°C per 5 n.mi. The southern boundary is represented by a weak front – the temperature drop between the Gulf Stream and the Sargasso sea waters is about 1 to 2°C.

Figure 23 <6> gives the results of experimental studies of long-range acoustic propagation along a track crossing the Gulf Stream from southeast to northwest. Explosive charges (TNT) were detonated at a depth of 244 m along the part of the path covering the Gulf Stream, 600 to 900 km away from two deep hydrophones located on the bottom near Bermuda. Received signals were analyzed in one-third octave bands centred at 50, 80 and 160 Hz. The sound-speed profile C(z) along the path was measured nearly simultaneously with the acoustical experiments.

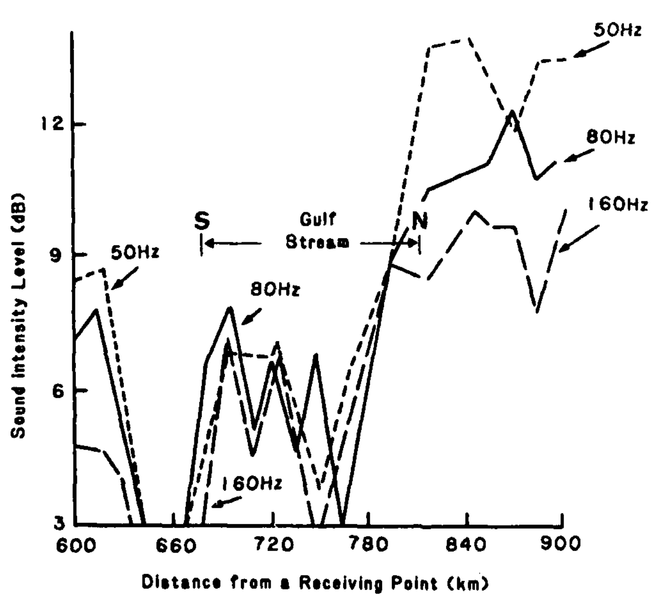


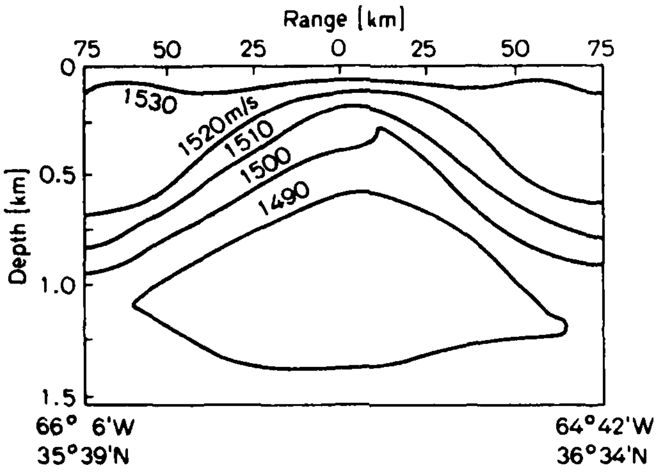
FIG. 23 SOUND INTENSITY LEVELS FOR PROPAGATION ACROSS THE GULF STREAM (From <6>) Sound intensity levels (normalized for attenuation and cylindrical spreading) vs range in one-third octave bands centred at 50, 80, and 160 Hz for propagation across the Gulf stream; N and S are north and south boundaries of the Gulf Stream.

The figure shows that the received levels were lowest when the charges were detonated near the southern and northern boundaries of the Gulf Stream. A strong variation of the level (6 to 10 dB) caused by a small shift of the position of the explosion is noticeable. The theoretical analysis showed that the observed features of the sound field can be explained by the variation of profile C(z) along the path, in particular by the increased depth of the sound channel axis between cold slope water and the warm waters of the Sargasso sea.

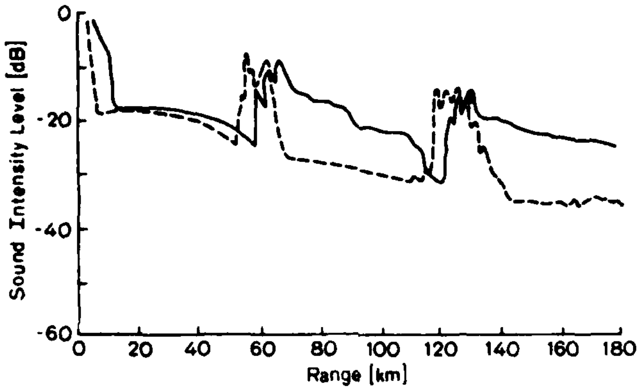
As a final example, reference is made to Fig. 24 <6>, which illustrates the effect on sound intensity of a cyclonic ring separated from the Gulf Stream. Figure 24a shows the distribution of sound-speed in a vertical plane. The isovelocity contours are elevated (as much as 700 m) in the central portion of the ring. As a result, the vertical gradient of the sound speed markedly increases towards the centre of the ring.

Figure 24b shows sound transmission loss versus range across the northern half of the cyclonic ring. The data were calculated using the ray approximation for a point omnidirectional source located in the centre of the ring at a depth of 200 m. The receiver depth is 300 m. The calculation of transmission loss takes into account wave-front spreading, absorption in the water, and leakage of sound energy into the bottom. For comparison, the transmission loss for the Sargasso Sea conditions outside the ring is also given. When sound propagates through the cyclonic ring, two features are observed: first, the removal of energy from the mid-depth channel to the deep sound channel due to the increased downward refraction of rays and the decrease of the sound intensity level; second, the decrease of the horizontal extent of the convergence zones and the displacement of their positions as compared with the standard position in the sound channel in the Sargasso Sea. At a depth of 1000 m, on the other hand, transmission loss curves show increased sound intensity levels (Fig. 24c). Analysis of the ray diagrams shows that effective sound propagation in the deep sound channel (z_m = 1000 m) arises in this case even if a sound source is located at a relatively shallow depth within the cyclonic ring. Thus, the cyclonic ring produces considerable perturbations of the sound field <6>.

a)



b)



c)

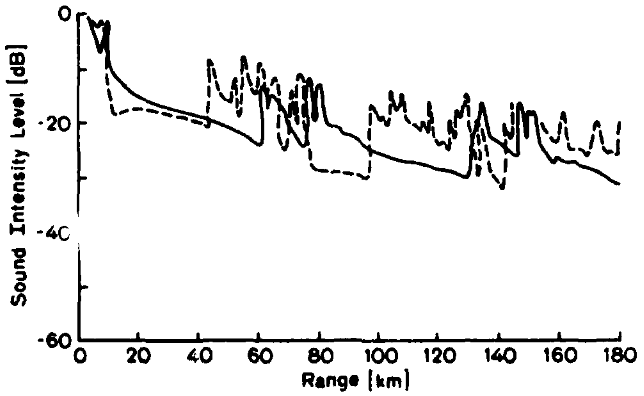


FIG. 24 EFFECTS ON SOUND INTENSITY OF A CYCLONIC RING SEPARATED FROM THE GULF STREAM (From <6>)

a) Sound isovelocity section in vertical plane passing through a cyclonic ring separated from the Gulf Stream. The numbers near curves denote the sound speed in m/s.

b) Sound intensity levels vs range for a receiver at a depth of 300 m. The solid curve corresponds to the Sargasso Sea ray diagram and the dashed curve represents the cyclonic ring ray diagram.

c) As in b) for a receiver at a depth of 1000 m.

4.1.3 Internal Waves and Smaller Scale Variations

The variations of interest in this category occur on time and space scales more comparable to the acoustic wave scales or observation scales of interest. That is, they occur on time scales of up to many hours and on space scales of up to kilometres in the horizontal and tens of metres in the vertical. Included in this group are internal/inertial waves, fine structure, microstructure, and turbulence. It is hardly possible here to provide more than a brief overview of this area.

Internal waves are ocean gravity waves made possible by the density increase with depth and the restoring force of gravity. They occur at the boundary between two fluids of different density, for example. The spatial and time scales vary widely - from 100 m to 10 km in the horizontal scale, 1 to 100 m in the vertical scale, and from 10 minutes to about a day in the time scale. Internal tides exist that are of lengths in the order of 150 km and have amplitudes of several metres in the open sea and somewhat larger on the continental shelf. Here, however, the shorter scale, more random internal wave motions are of interest. Their natural frequencies lie between the inertial (or Coriolis) frequency, $\omega_i = 2\,\Omega\,\sin\phi$, and the buoyancy (i.e. Brunt-Väisälä) frequency

$$n(z) = \left[-g/\rho\,\frac{d\rho}{dz} - g^2/c^2\right]^{1/2},$$

where

Ω is the earth's angular velocity,

ϕ is the local geographic latitude,

g is the acceleration due to gravity,

c is the speed of sound.

The inertial frequency varies from zero at the equator to $2\,\Omega = 2\pi/(12\text{ hours}) = 1.46\times10^{-4}/\text{s}$ at the poles. The buoyancy frequency varies typically from 3 cycles per hour near the surface to 0.2 cycles per hour near the bottom.

Internal waves have a significant effect on sound propagation. They constantly perturb the sound speed field by displacing and distorting the isovelocity profiles, thereby causing stochastic variations in the phase and amplitude of the acoustic signal. Internal waves have received considerable attention in recent years, both because of their importance in acoustics and also because, apart from surface waves, they are the only ocean process for which an appropriate statistical representation (the Garrett-Munk (GM) model) is available. Indeed, they have become so "fashionable" that there is some question as to whether they have not been overused as an explanation of fluctuations. A number of examples of the effects of internal waves are presented below.

Figure 25 <25> shows the effect on isotherms of the passage of internal waves. The top curve features tidal periodicities of predominantly 12 hours, while the bottom features shallow-water phenomena and reveals prominent cycles of about 15 minutes duration. Generally, a spectrum of frequencies is present. This is clearly indicated in Fig. 26 <26>, which

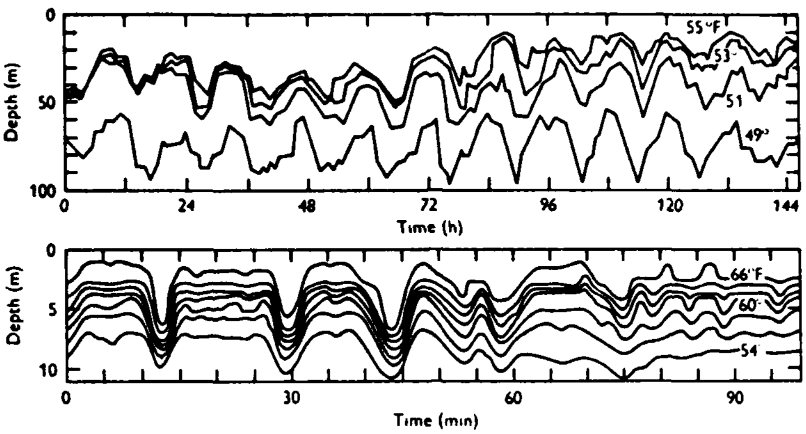


FIG. 25 ISOTHERMS IN INTERNAL WAVE MOTIONS (From <25>)
Isotherms in internal wave motions. (Top) dominant component with tidal frequency and amplitude about 15 m. (Bottom) Oscillations in a shallow thermocline with a considerably higher dominant frequency

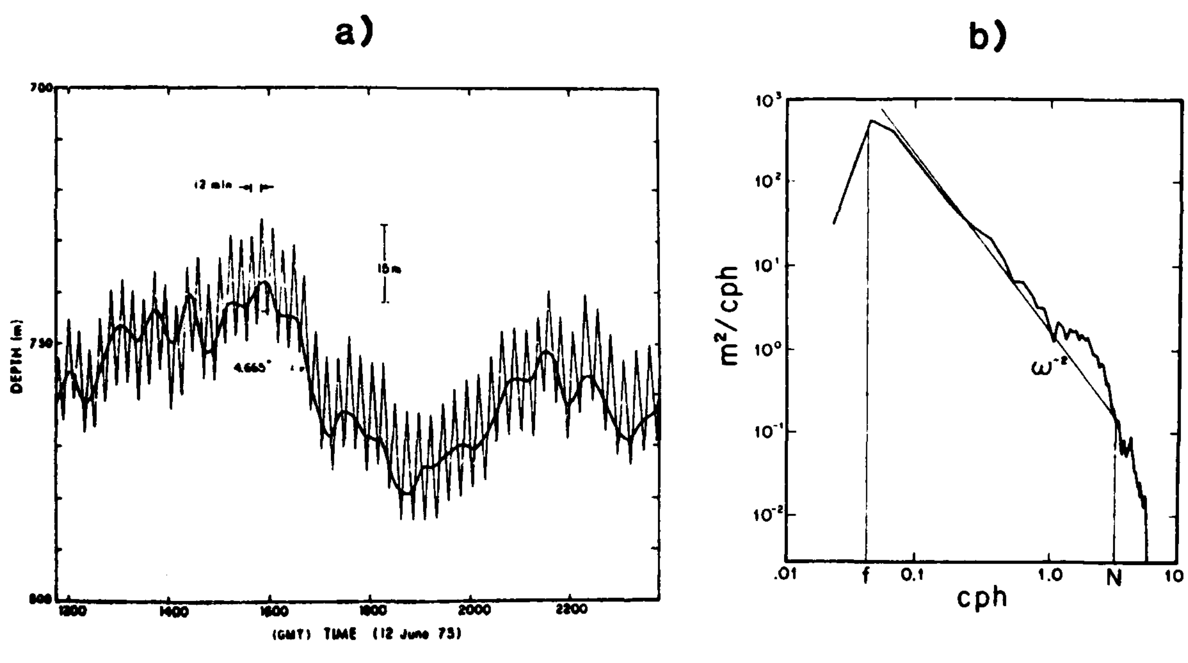


FIG. 26 VERTICAL DISPLACEMENT OF AN ISOTHERM BY AN INTERNAL WAVE (From <26>)
a) The heavy line shows the depth of a particular isotherm, measured by a drifting instrument package, yo-yoing vertically as shown by the zig-zag lines (Cairns 1975).
b) Power spectrum of vertical displacement of an isotherm (Cairns and Williams, 1976).

shows a) the fluctuation in depth of a particular isotherm and b) the resulting power spectrum of its vertical displacement. The significant drops in energy below the Coriolis frequency and above the Brunt-Väisälä frequency, here denoted by f and N respectively, suggest that the fluctuations are due to internal waves. Additional evidence confirms this conclusion.

The complexity of the vertical structure associated with internal wave currents is shown in Fig. 27 <26>. The vertical scale can essentially be interpreted as representing depth in metres, since a decibar corresponds closely to 1 m of depth. As seen, the horizontal currents are typically 0.05 m/s. Much of the current reverses in half the inertial period.

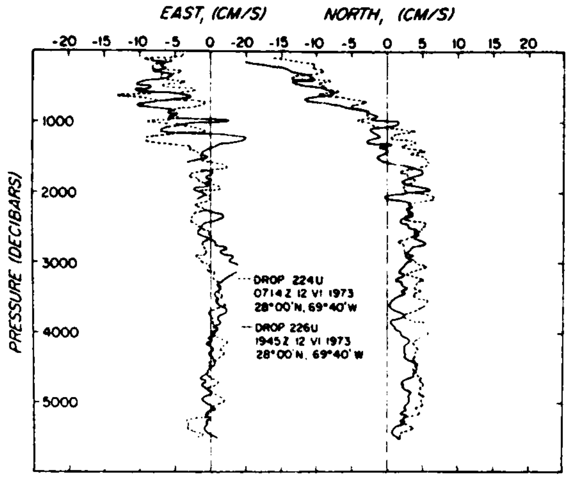


FIG. 27 VERTICAL PROFILES OF INTERNAL WAVE CURRENTS (From <26>)
Vertical profiles of eastward and northward currents at an interval of 12.5 h at a fixed location. A decibar corresponds closely to 1 m of depth.

Environmental fluctuations induced by internal waves are not, of course, confined to the temperature parameter. An example of fluctuations in salinity is shown in Fig. 28 <20>. This observation indicates an internal wave of 150 m depth with an amplitude of about 100 m and a period of about half a day.

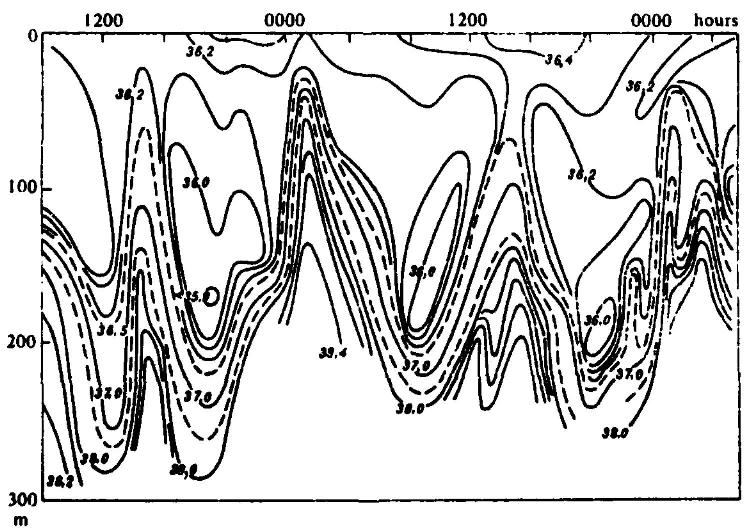


FIG. 28 SALINITY FLUCTUATIONS INDUCED BY INTERNAL WAVES (From <20>)
Salinity fluctuations (in ‰) in the Strait of Gibraltar (35°54.6'N, 5°44.4'W) on 16-18 May 1961.

Examples of the effects of internal waves on acoustic propagation are shown in Figs. 29 <27> and 30 <6>. Figure 29 shows temporal fluctuations of the (a) amplitude and (b) phase of a 367 Hz signal recorded at a range of 1318 km. The source was located at a depth of 527 m on the bottom slope near Eleuthera (Bahamas), and the receiver was at a depth of 1723 m on the bottom near Bermuda.

Figure 30 presents amplitude and phase-rate spectra for a single frequency experiment at 220 Hz performed southeast of Bermuda. The phase rate, $d\phi/dt$, is single valued and therefore is preferred, as an estimator, to the multivalued phase. For the experiment, a 220 Hz sound source was moored on the axis of the deep sound channel, at a depth of 1100 m, and data were collected on hydrophones suspended at depths of 500, 1000, and 1500 m from a drifting ship, at a range of about 250 km from the source. The drift rate averaged 500 m/h along the propagation path for these data. Runs at different depths were taken in random order over a three-day interval. The phase-rate spectra fall monotonically, at a rate between $\omega^{-0.5}$ and ω^{-1}. The spectra from the deeper hydrophones fall off somewhat more rapidly. The amplitude spectra fall monotonically as $\omega^{-1.5}$. The solid lines are theoretical results based on a random multipath model of sound propagation developed by Dyson et al using the Garrett-Munk model of internal waves.

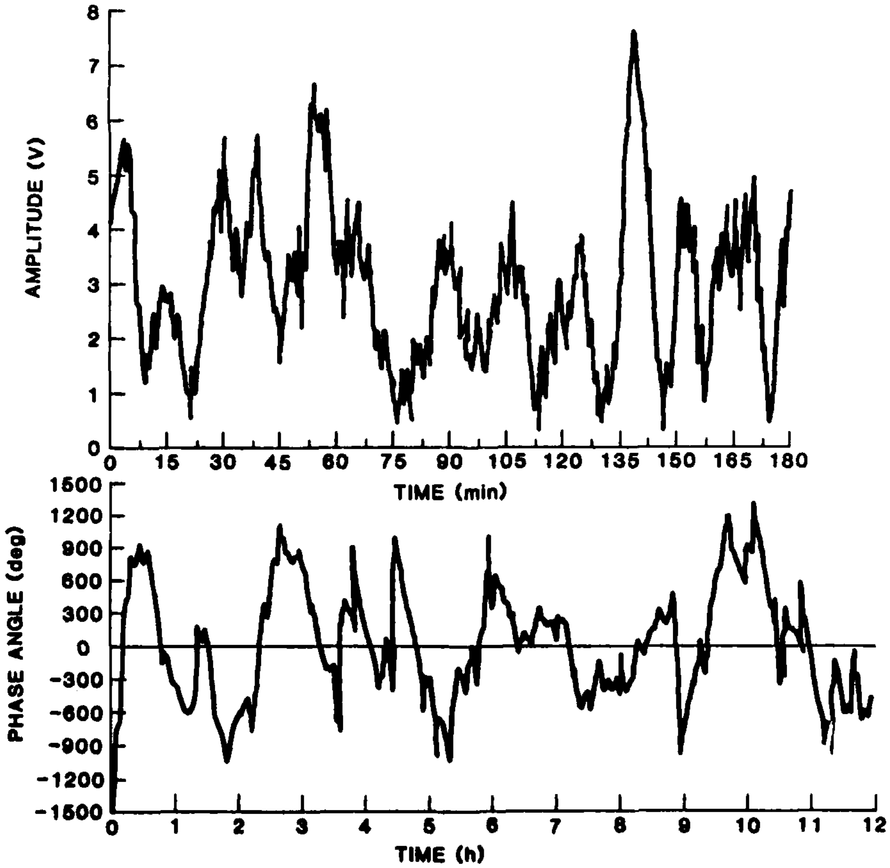


FIG. 29 ACOUSTIC AMPLITUDE (a) AND PHASE (b) FLUCTUATIONS INDUCED BY INTERNAL WAVES (From <27>)
367 Hz signal at range of 1318 km. Source at 527 m near Bahamas receiver at 1723 m near Bermuda.

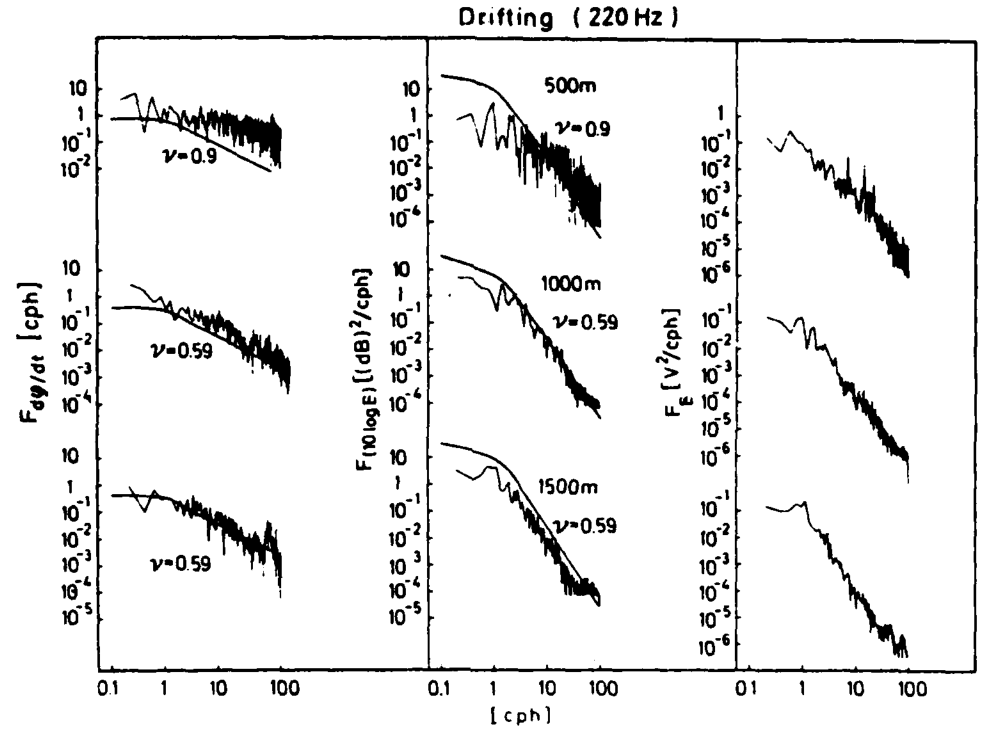


FIG. 30 ACOUSTIC AMPLITUDE AND PHASE-RATE SPECTRA (From <6>)
Frequency spectra of 220 Hz sound signal fluctuations: Phase-rate (dϕ/dt) spectra on the left; spectra of the log amplitude (10 log E) in the middle, and amplitude (E) spectra on the right. Smooth curves are predictions based on a random multi-path model.

On a slightly smaller spatial scale, the region of fine structure occupies vertical lengths of one to several tens of metres and horizontal lengths of tens to many hundreds of metres. Fine structure is usually characterized by "sheets" and "layers" in the vertical profiles of density or temperature. This step-like, discontinuous structure may also apply to salinity and current speed. The values of the vertical gradients of the temperature and salinity at the boundaries of layers may exceed the values of their mean gradient by one or two orders of magnitude. The vertical gradient of the current speed may reach the significant value of 2 cm/s per metre of depth, and in some cases even 5 to 10 cm/s per metre of depth in boundary layers <6>. An example of the steplike structure in temperature, salinity, and sound speed is indicated in Fig. 31 <25>. The fine-layered structure of the ocean can considerably influence the sound fields.

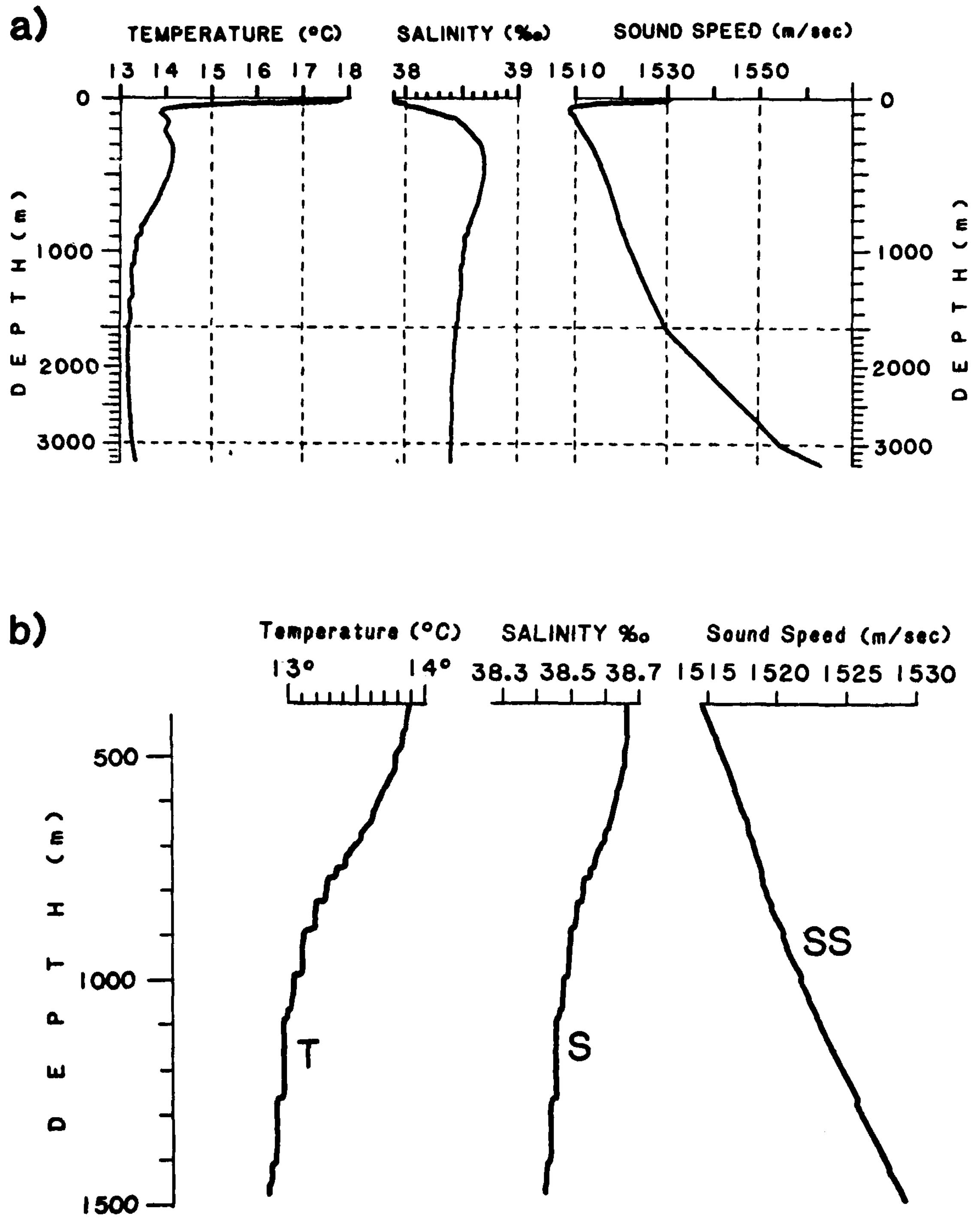


FIG. 31 STEP-STRUCTURE IN TEMPERATURE, SALINITY, AND SOUND-SPEED PROFILE (From <25>)
a) Gross profiles of temperature, salinity, and sound speed.
b) Magnified profiles for 400 to 1500 m depths showing layered microstructure. (Mellberg and Johannessen, 1973).

Vertical gradients of the current speed at boundaries of layers can become comparable to vertical gradients of the sound speed. This can significantly change the trajectory of sound rays if their direction at this level is close to horizontal. An example is provided by Fig. 32 <6>. Figure 32a shows the simple environmental-acoustic model used by Sanford <28> to calculate the effect of ocean current on sound propagation. The sound-speed profile was observed in the Sargasso Sea. The current speed is equal to zero everywhere, except in the layer between 250 m and 400 m. A sound source is located at a depth of 350 m. Figures 31b and c show ray diagrams for sound propagation in the direction of the current and against the current.

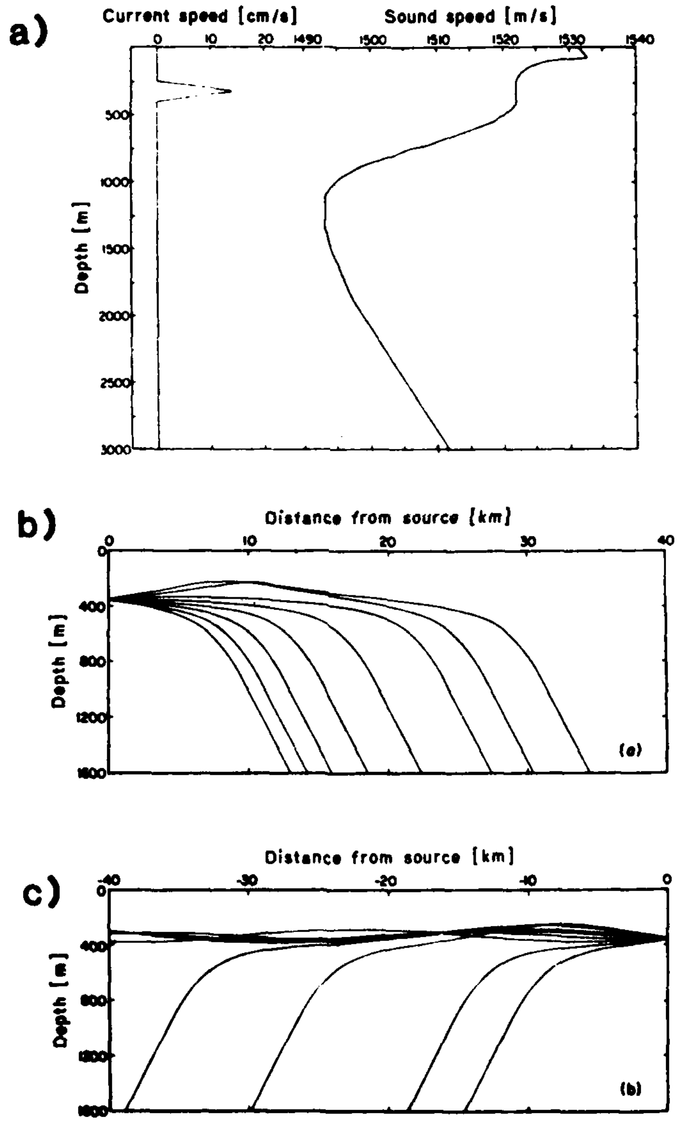


FIG. 32 EFFECT OF OCEAN CURRENT ON SOUND SPEED PROPAGATION (From <6>)
a) Current and sound speed model used to compute refraction.
b) Ray diagram for sound propagation with the current.
c) Ray diagram for sound propagation against the current.

Observations have shown that the fine-layered structure of ocean water can lead to multipath propagation even in cases where, in the absence of fine structure, only one ray would arrive at the receiver. This, in turn, leads to phase and amplitude fluctuations in the acoustic signal. The mechanism giving rise to fine structure is thought to be internal waves. Further, because of the overlap in spatial scales with internal waves, the statistical representation of data has generally been similar to that of internal waves, i.e. the calculation of spectra.

At smaller scales of variation – centimetres in the vertical and many metres in the horizontal – is the so-called microstructure range. These scales are difficult to observe, but the mechanisms for generation and maintenance of the microstructure are believed to be similar to those for fine structure.

Turbulence is usually included in the microstructure range. In fact, it has been suggested that temperature and salinity microstructure is sometimes the residue from a turbulent event after the turbulence velocity microstructure has dissipated. These small-scale fluctuations are significant at high frequencies – i.e., about 5 kHz and higher.

It is important to note that the terminology of the ocean structure is an evolving one, since it is based largely on instrument resolution, which has improved with the passage of time.

4.2 Tidally Induced Acoustic Fluctuations

As a final example of acoustic fluctuations that are explicitly linked with environmental variations, we consider tidal variations. Here, too, we must be selective, since tidally induced acoustic fluctuations have been observed by numerous investigators under a wide variety of experimental conditions. Moreover, there are several different aspects to tidal phenomena. In particular, as pointed out by Weston et al <22>, there are essentially four different mechanisms, which together produce three types of acoustic effects. The mechanisms are the tidal changes in water depth, tidal streaming, depth dependence of tidal streaming, and tidal changes in water structure. The effects concern signal amplitude, phase, and character, and are usually greater for shallow water.

Tidal changes in water depth affect the modal interference pattern, since the latter depends on depth. The tidal changes effectively sweep this pattern past the fixed receiver, converting spatial variations into temporal variations. The effect produces fluctuations in the amplitude and phase of an acoustic signal. The short-range effects sometimes show the expected symmetry about high or low water, and there are amplitude variations of up to 30 dB. The number of interference peaks swept through increases with range, so the mean fluctuation period at longer ranges is much shorter than the tidal period. Changes in water structure and tidal streaming tend to destroy the perfect symmetry of the interference patterns and thereby affect both the amplitude and the phase delay of an acoustic signal.

An example of the fluctuation in amplitude is provided by Fig. 33 <2>, which shows fluctuations of 10 to 15 dB over a distance of 1524 m (5000 ft) in 18 m (60 ft) of water that occurred simultaneously with a 0.6 m (2 ft) range of the tide. Figure 34 <2> shows fluctuations in phase of a 420 Hz cw signal transmitted between Miami (Florida) and Bimini (Bahamas). Apart from the strong diurnal variability of phase, the effect of the passage of a cold front (marked by an arrow) is also shown in the figure. Not surprisingly, the phase delay (number of cycles between source and receiver) is increased by the cold front, which is consistent with Weston's observations (Sect. 4.1.1). The correlation between tidal phenomena and acoustic fluctuations, particularly in the phase of acoustic signals, has been extensively studied in the region between Eleuthera (Bahamas) and Bermuda by project MIMI (Miami/Michigan Universities) and also in the Straits of Florida. The results indicate that the characteristic features of the acoustic fluctuations are similar in both areas. In particular, the fluctuations of amplitude with time are noise-like with deep fades typical of multipath propagation. Phase, on the other hand, shows tidal variations and long-term trends. However, the tidal modulations observed from Eleuthera to Bermuda are semi-diurnal rather than diurnal as observed in the Straits of Florida.

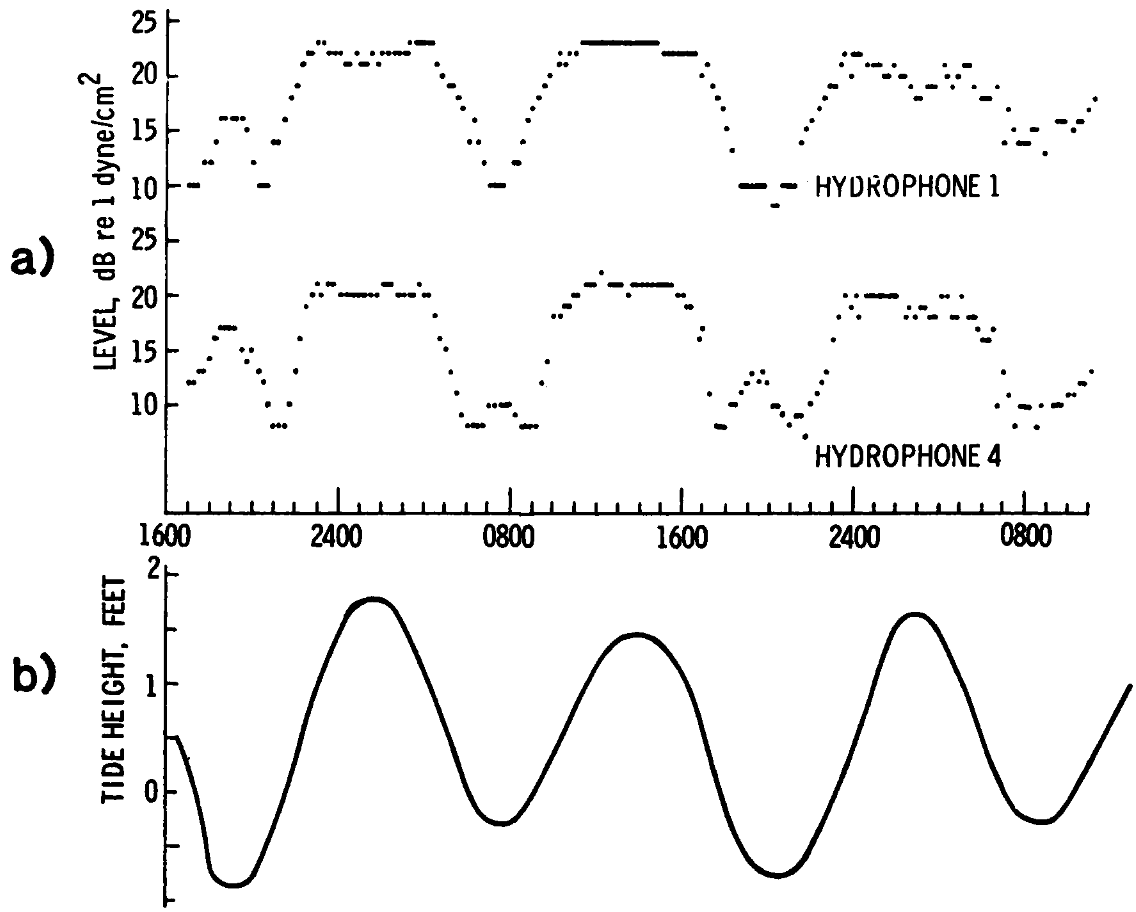


FIG. 33 TIDALLY INDUCED ACOUSTIC AMPLITUDE FLUCTUATIONS (From <2>)
a) Level of 1120 Hz cw transmission over a distance of 5000 ft (1.5 km) to two hydrophones 100 ft (30.5 m) apart.
b) Tidal cycle in 60 ft (18 m) of water.

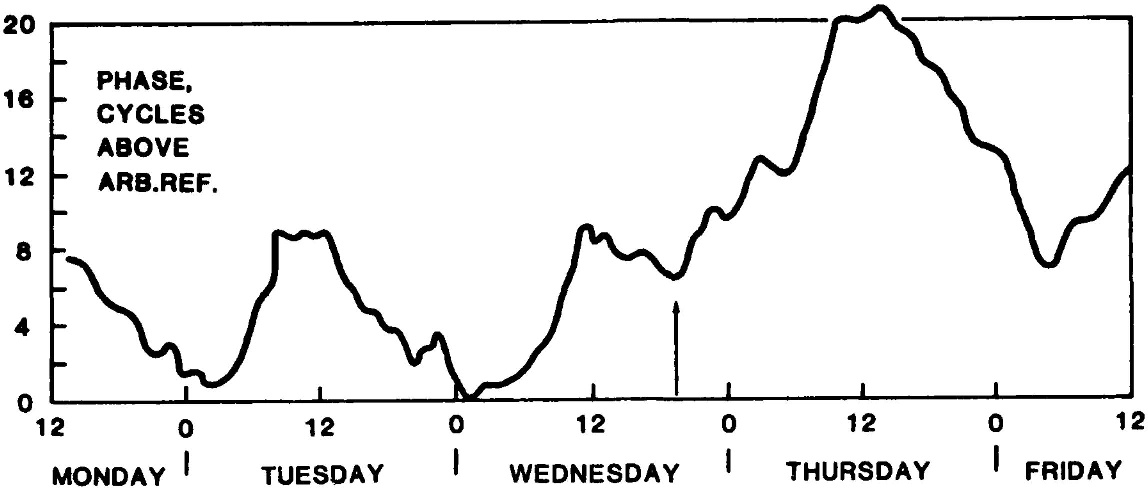


FIG. 34 TIDALLY INDUCED ACOUSTIC PHASE FLUCTUATIONS (From <2>)
Phase changes in 420 Hz transmission over a distance of 41 mi between Florida (Miami) and the Bahamas (Bimini). The transmission paths are refracted-bottom-reflected. The arrow marks the passage of a cold front.

Figure 35 <4> shows a comparison between the acoustic phase and the transport of water by the Gulf Stream. It is seen that both vary with the daily tides. Figure 36 <4> shows the measured variations in amplitude and phase of a 420 Hz acoustic signal at a 7-mile hydrophone during one tidal cycle.

For a final example of tidal effects, we refer again to Fig. 19 <22>, repeated here as Fig. 37 for convenience. The influence of the semi-diurnal tide is very clear in both the amplitude and the phase records. The change in amplitude from neaps (minimum tidal amplitude) at the beginning of the record to nearly springs (maximum tidal amplitude) at the end is quite evident, as is the excellent agreement between prediction and measurement. The irregularities in the measured results are presumably attributable to modal interference effects.

Table 1 summarizes the highlights of the environmental effects discussed in this chapter.

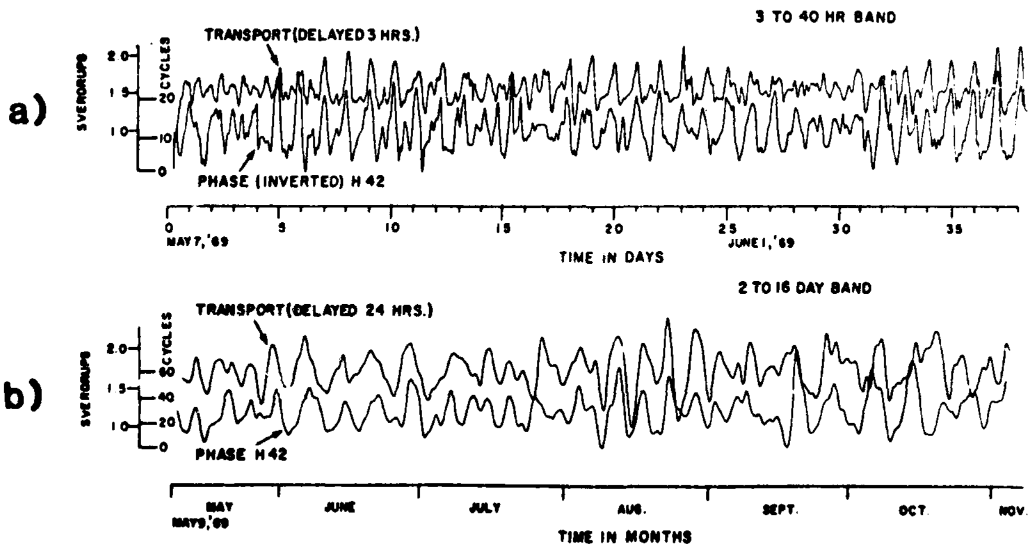


FIG. 35 COMPARISON OF WATER TRANSPORT AND ACOUSTIC PHASE IN THE GULF STREAM a) 3 to 40h band, b) 2 to 16 day band. (Steinberg et al) (From <4>)

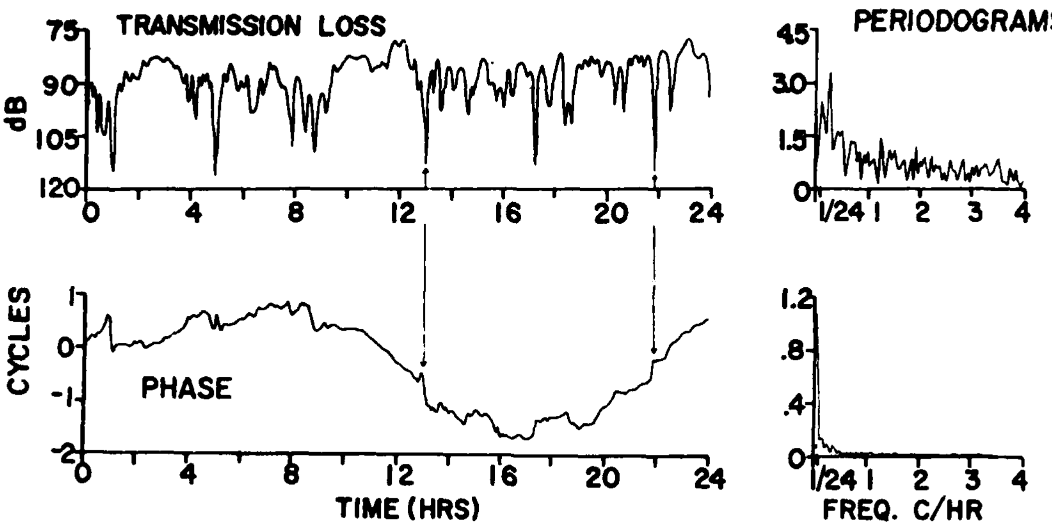


FIG. 36 VARIATIONS IN ACOUSTIC AMPLITUDE AND PHASE DURING A TIDAL CYCLE (From <4>)
Observed variations of amplitude and phase of a 420 Hz at a 7-mi hydrophone during one tidal cycle.

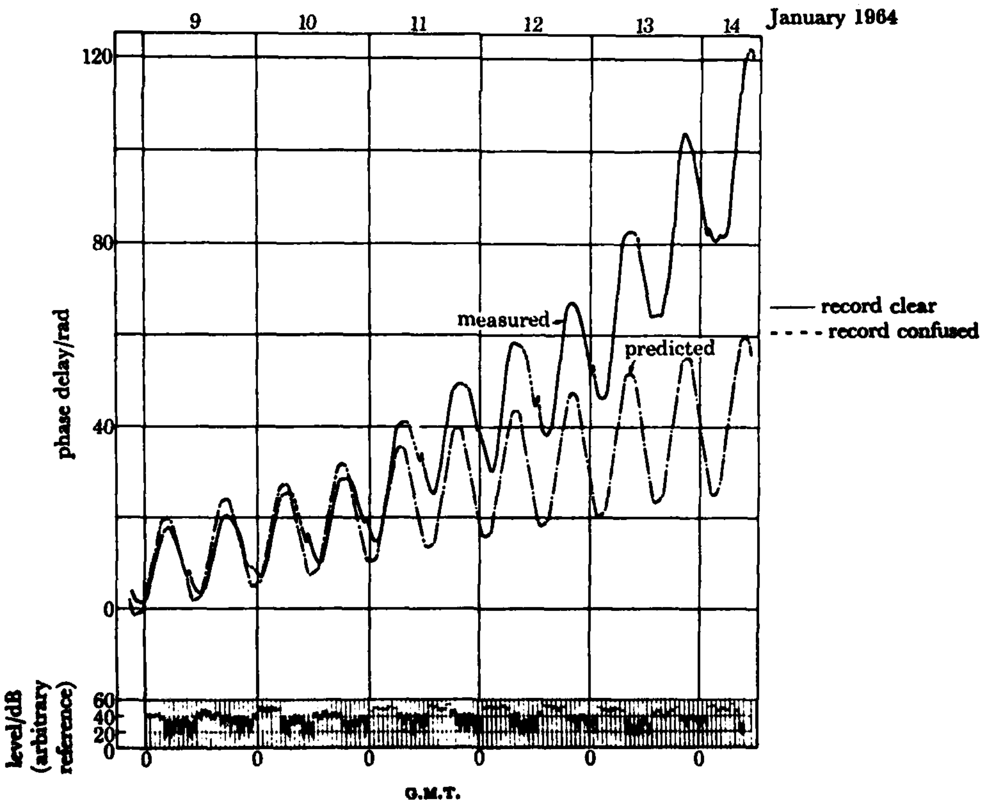


FIG. 37 EFFECT OF SEASONAL CHANGES ON THE PROPAGATION OF A CW ACOUSTIC SIGNAL (From <22>) (Repetition of Fig. 19)
January 1964 fluctuations: measured and predicted phase curves and recorded amplitude samples (2083.3 Hz, 7.8 km, 047°).
1 min samples taken each hour for amplitude record.

TABLE 1

ENVIRONMENTAL PHENOMENA AND THEIR ACOUSTIC EFFECTS

Phenomenon	Spatial Scales		Temporal Scales	Comments	Acoustic Parameter Affected
	Horizontal	Vertical			
Ocean Climate (General Circulation)	Up to entire Ocean Basin	A few 100 m	Seasonal	·Greatest variability occurs in surface layers	·Acoustic amplitude ·Acoustic phase ·Propagation path
Mesoscale (Ocean Weather)	50 to 500 km	Up to Ocean depth	Days to months	·Includues eddies and fronts. ·Deterministic perturbations from mean structure	·Propagation path ·Acoustic intensity ·Signal travel time ·Signal shape
Internal waves	100 m to 10 km (can be much larger)	1 to 100 m	10 min to approx. 1 day	·Frequency spectrum bounded by inertial frequency at low end and Brunt-Väisälä frequency at high end. ·Random perturbation from mean structure	·Acoustic amplitude ·Acoustic phase ·Significant effect on nearly horizontal ray paths.
Fine structure	10's to 100's of m	1 to 10 m		·Characterized by step-like structure in temperature, density, salinity, current. Statistical representation similar to that for internal waves	·Propagation paths ·Phase fluctuations ·Amplitude fluctuations
Microstructure	Many metres	Centimetres		·Generation mechanism similar to that for fine structure. ·Includes turbulence.	·Scattering of high frequency (5 kHz and higher) waves. ·Fluctuations in acoustic amplitude and phase.
Tidal	Variable	Wave height can exceed 10 m, but subsurface effects may extend to greater distances	Diurnal and semidiurnal	Includes the following mechanisms: ·Tidal changes in water depth. ·Tidal streaming. ·Depth dependence of tidal streaming. ·Tidal changes in water structure (including the introduction of tidal-period internal waves)	·Acoustic amplitude fluctuations are generally noise-like ·Acoustic phase fluctuations are simply correlated with tidal variations. ·Acoustic effects are greater in shallow water.

5 ACOUSTIC VARIABILITIES CAUSED BY SOURCE/RECEIVER MOTION

The fluctuation results discussed so far were generally obtained from experiments in which both the transmitter and the receiver were fixed. Under such circumstances, measured acoustic fluctuations are more easily associated with environmental fluctuations and/or multipath propagation. When either the source or the receiver, or both, are moving the situation is generally more complex. Indeed, in this situation, it is often difficult to separate environmentally induced acoustic fluctuations from those arising from source/receiver motion. Moreover, in many cases the fluctuations arising from source/receiver motions are far greater than those due to the environment.

An example of motionally induced fluctuations is shown in Fig. 38 <2>. This shows the signal received by sonobuoys at two depths, 27 m (90 ft) and 91 m (300 ft), from a steady two-frequency (142 and 275 Hz) source as it was towed at a speed of 2.7 kn out to the first convergence zone. The propagation here is by bottom/surface multipath. There is little evident correlation of the envelope of the received signal between the two depths at the same frequency or between the two frequencies at the same depth. Also, there is a wide range of fluctuation periods, from fast unresolved fluctuations to slow signal surges lasting about one hour; the effect of a faster towing speed would doubtless be to speed up the fluctuations. For the 142 Hz cw data illustrated in Fig. 38, the auto-correlation coefficient of signal samples integrated over 16 s was found to fall to 1/e (0.368) in times ranging from 0.25 min (no correlation between successive samples) to 7.5 minutes, with a tendency for the correlation time to increase with range. In short, in these data the many transmission multipaths interfered in a complex and constantly changing manner as the range between source and receiver increased <2>.

Another example of motion-induced fluctuations was provided in connection with the SACLANTCEN experiment of Sevaldsen (see Figs. 5, 6). In particular, it was shown that the usefulness of the scattering function is greatly diminished in the presence of source or receiver motions, since these motions tend to mask the effects of variability in the medium.

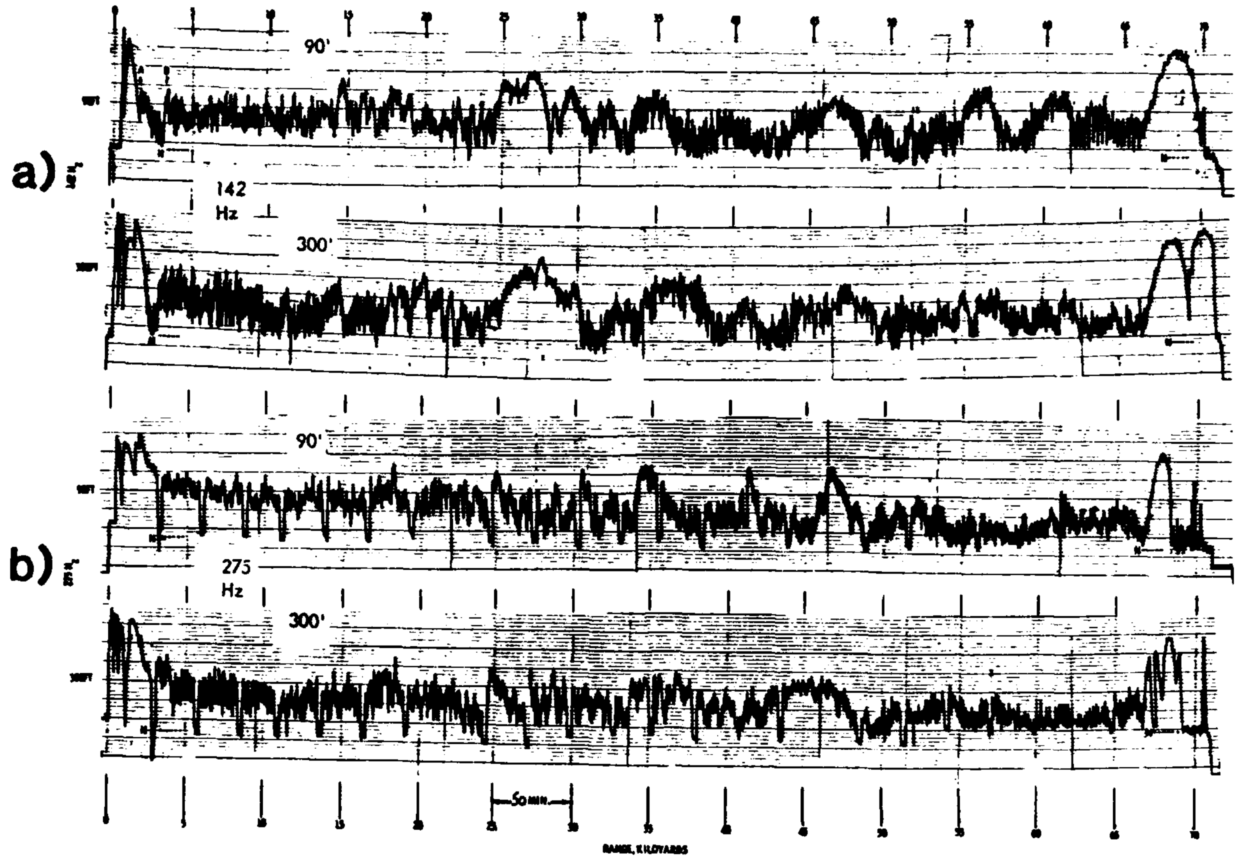


FIG. 38 MOTION-INDUCED ACOUSTIC AMPLITUDE FLUCTUATIONS (From <2>)
Level vs range of a) 142 Hz and b) 275 Hz signals from a common source towed out to the first convergence zone. Each signal is shown as received at two depths: 27 m (90 ft) in the upper plot and 91 m (300 ft) in the lower plot.

6 SUMMARY OF MECHANISMS FOR ACOUSTIC VARIABILITY

According to Urick <2> the underlying cause of fluctuations in acoustic signals is multipath propagation in an inhomogeneous moving medium. In the present report many of the known mechanisms have been identified in a less generic way. Their temporal aspects are summarized in Fig. 39. Tre reports of Sykes <4> and Weston et al <22> give additional mechanisms, not explicitly considered in this report, including Rossby waves (planetary waves), solar heating, changes in tidal phenomena resulting from changes in lunar declination, movements of large air masses, fish activity, and so forth. Clearly, the number and degree of influence of these effects will vary greatly from experiment to experiment. An example is provided by Table 2 <22>, which lists mechanisms considered to be important in a series of shallow-water measurements conducted off the British isles by Weston et al. According to Weston, the division into nine mechanisms was somewhat arbitrary and incomplete. He further states that "part of the fluctuation energy with periods between a minute and an hour is due to mechanisms (e), (f), and (h), but possibly not all. The rest may be due to long surface waves, internal waves, bodily water movements, turbulence, etc. – but it is extremely difficult to prove any of these hypotheses." Subsequent analysis of the data has apparently confirmed the role played by internal waves <29>.

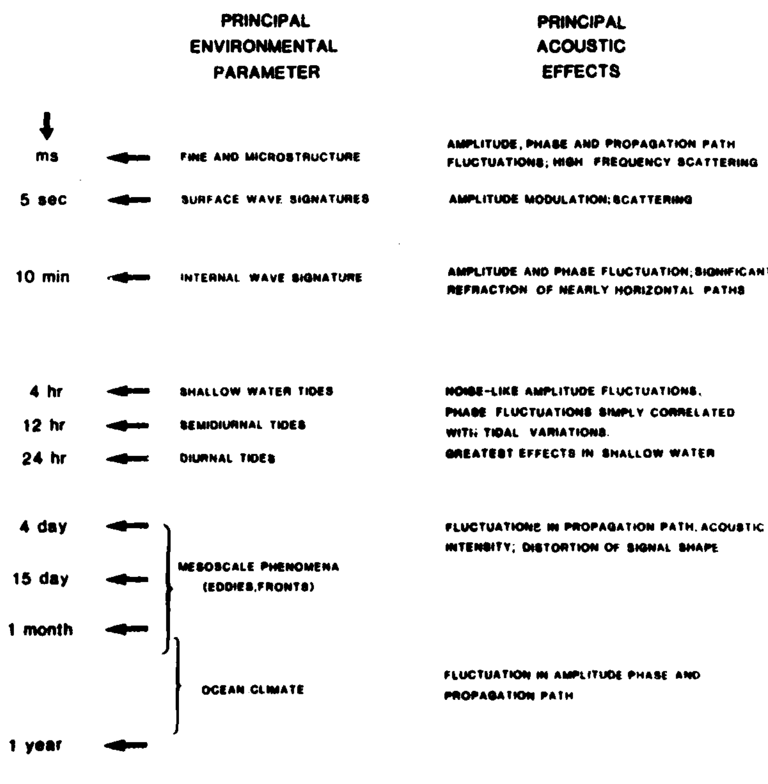


FIG. 39 TEMPORAL VARIATIONS OBSERVED IN ACOUSTIC DATA

TABLE 2 (after <22>)

FLUCTUATION MECHANISMS IN COASTAL WATERS OF THE BRITISH ISLES

	Mechanism	Predominant Period	Parameter Affected	Comment
a	Seasonal change in conditions temperature structure, fish population, etc.	One year	Mainly amplitude	Transmission is best in winter
b	Seasonal change in mean temperature	One year	Mainly phase	Phase delay is greatest in winter
c	Fish shoaling	One day	Amplitude	The level changes often occupy only about 10 minutes near dusk and dawn
d	Storms	Order of several hours	Mainly amplitude	Transmission is reduced by the extra scattering loss, etc.
e	Changes in water depth	Tidal	Amplitude and phase	The changing mode interference patterns cause fluctuations at the tidal period or its harmonics
f	Depth-dependence of streaming velocity	Tidal	Amplitude and phase	The mode parameters can be greatly changed (especially above 2 kHz), causing fluctuations as in e
g	Changes in mean streaming velocity	Tidal	Phase	The phase delay is a direct measure of the resolved velocity components
h	Includes fish	A few minutes	Amplitude and phase	See <22> for complete list
i	Surface waves	Many seconds	Amplitude and phase	The magnitude of the effects is largely controlled by mechanisms e and f

CONCLUSIONS AND RECOMMENDATIONS

1) General

The objectives of this paper are twofold. First, to present the results of a short-term, but fairly intensive perusal of relevant literature on the subject of variability in acoustic signal transmissions. Second, to suggest, on the basis of the preceding, areas of variability studies wherein SACLANTCEN might usefully conduct further investigations.

Most of the paper is, by necessity, devoted to the first objective. Prior to listing more particular conclusions, a general observation concerning the use of the term "fluctuations" is in order. As indicated in the Introduction, the term is used generally to denote both temporal and spatial variations in either environmental parameters or acoustic levels. As such, the term includes the effects of a host of diverse, often unrelated, phenomena. Such an all-embracing use of the term is not very helpful, any more than a similar propensity on the part of some investigators to see the effects of internal waves in every measurement. It is clear from the literature that a number of interesting and important sources of acoustic transmission variability exist and should be investigated further. However, the continued imprecise use of the term "fluctuations" will probably ensure that a good deal of effort will, instead, be expended on the attempt to understand what is already understood. It is clear, for example, that a source towed through a convergence zone will result in significant acoustic fluctuations at a distant receiver. There is nothing remarkable about this. Fifty similar measurements of the same phenomenon will make the existence of these fluctuations no more remarkable, only consistent. On the other hand, after accounting for this effect, and other known effects, any additional fluctuations will be of greater interest. It is suggested then, that some agreement be achieved whereby the term "fluctuations" be used more constructively and not, as at present, as a catch-all expression hiding a host of known and unknown mechanisms.

2) Aspects already studied

Certain aspects of acoustic fluctuations have received a good deal of attention, while for others the literature is rather sparse. Among the most studied acoustic fluctuations are:

(a) Those between a fixed source and fixed receiver over fairly long ranges (e.g. the Straits of Florida and Eleuthera-Bermuda experiments).

(b) High-frequency fluctuations over a direct path or paths (Bristol Channel, U.K.).

(c) Surface reflections.

Areas of variability that have, as yet, received considerably less attention include:

(a) Motion-induced fluctuations.

(b) Low-frequency, long-range acoustic propagation fluctuations.

(c) Shallow-water fluctuations.

(d) Long-range spatial variations, etc.

Frequencies and ranges associated with some of the most studied areas are as follows:

(a) Straits of Florida experiment: range 7 to 42 n.mi., frequencies around 400 Hz.

(b) Eleuthera-Bermuda: range 550 and 1250 km, frequencies around 400 Hz.

(c) Bristol Channel: range between 2 and 137 km, frequencies approximately 1, 2, 3 kHz.

(d) Cobb Seamount: range 17.2 km, frequencies 4, 8 kHz.

3) Current Knowledge of Mechanisms

A great deal has been accomplished in enumerating the possible causes of acoustic fluctuations. Tables 1 and 2 and Ch. 6 provide details. Relevant general observations include the following:

(a) While it has been possible to enumerate possible causes of acoustic fluctuations, it has often not been possible to isolate the dominant one(s) in particular measurements.

(b) The fluctuation of lower frequency acoustic signals are more indicative of dynamic ocean events than are higher frequency signals. Lower frequency signals are characterized by relatively stable phase and random amplitude.

(c) CW transmission studies (particularly by the MIMI group and Weston et al) have established the strong and clear correlation between environmental changes (particularly seasonal and tidal) and acoustic signal phase. Signal amplitude, on the other hand, is not as simply related to ocean dynamics.

(d) Source and/or receiver motions can cause significant fluctuations in received acoustic signals. Further, the problem of separating environmentally induced fluctuations from those due to the source/receiver motion is very difficult in most situations.

(e) Internal waves as an explanation of acoustic fluctuations have received considerable attention. The Garrett-Munk theory of internal waves has been successful in explaining some results.

(f) The fluctuations associated with shallow-water propagation are greater, and less easily associated with particular mechanisms, than those for deep-water propagation.

4) Recommendations on Future Studies

Based on the preceding, several areas of potential study suggest themselves. In particular, the following general topics warrant further consideration.

(a) Low-frequency, long-range acoustic propagation fluctuations.

(b) Spatial variations in transmission loss.

(c) Measurement of internal wave effects in shallow-water propagation.

(d) Quantitative identification of the different fluctuation mechanisms and their correlation with ocean processes.

(e) The role of ambient noise in fluctuations.

(f) The effect of fluctuations on signal structure, i.e. on the temporal and spatial coherence of the signal.

(g) Investigation of signal phase as an indication of environmental conditions, particularly over long-range propagation paths.

Clearly, the above are not mutually exclusive items. The elucidation of one item will most probably shed light on one or more of the others. Thus, item f, for example, will involve considerations of signal distortion, and not merely amplitude changes. In other words, the coherence of the signal, both in time and space, will be of interest and not merely its amplitude fading. By necessity, such an investigation will involve the phase stability of the signal, item g.

Item d is meant to suggest the need for greater correlation between studies of suspected fluctuation mechanisms and the underlying physics as indicated by the results of mathematical models. The Garrett-Munk theory is an example of a reasonably successful model of internal waves for deep-water propagation; this model does not, apparently, apply to shallow-water conditions <30>. An attempt to develop, or apply, models of internal-wave fluctuations in shallow-water conditions will require a reliable data base, as envisioned in item c. More generally, what is envisioned as the outcome of item d is the delineation of expected fluctuation levels, within specified frequency bands, for each known mechanism. With reference to Fig. 39, for example, this would enable one to expect, *a priori*, that for each mechanism the transmission loss (TL), say, be given by $\overline{TL} \pm \sigma$ (dB) for the frequency range $f_1 \leq f \leq f_2$, where the mean TL ($\overline{TL}$), fluctuation range (σ), and frequency range would depend on the particular mechanism being considered. Similar considerations apply to the other fluctuation mechanisms.

Item e – the role of ambient noise – involves an area of some significance. Surprisingly, it appears to have received little attention, *per se*, in the fluctuations literature. In reference to acoustic transmission, an important question concerns the degree to which the acoustic signal can be separated from the noise. In other words, can the signal and noise fluctuations be isolated, or must the composite signal-to-noise be treated as one fluctuating process? To answer this question and other questions concerning noise requires greater understanding of the noise statistics. In particular, the noise parameters to be understood include the temporal and spatial correlation functions of the noise, the statistical distribution of its amplitude fluctuations, and the mean level of omnidirectional ambient noise.

An understanding of the topics listed above will require careful analysis of acoustic data and relevant mathematical models. Some of those data have already been provided by previous SACLANTCEN shallow-water propagation experiments. Analyses of these data for fluctuation information would seem to be a reasonable beginning. Subsequently, and based on an enhanced

understanding, presumably to be derived from the data analyses, the questions listed above may be further refined and used as the basis for a carefully designed experiment on fluctuations in acoustic transmission. Due to the nature of the problems, such an experimental programme potentially involves large geographical areas and several related experiments.

It is clear from the literature that a large emphasis has so far been placed on range-dependent fluctuations, generally over diverse areas. While not neglecting this aspect, measurements of temporal fluctuations, particularly in selected geographical areas, should also be emphasized. As examples of the types of measurements of potential interest, we may cite temporal fluctuation studies near particular straits, in the vicinity of strategic "choke points", or for entire basins.

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